Rehabilitation Research and Development Center

1988

Veterans Administration
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Palo Alto, California 94304

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Rehabilitation Research and Development Center

1988 Progress Report

Veterans Administration Medical Center
Palo Alto, California

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Editor's note:

The reports in this document reflect work completed or in progress between January 1986 and January 1988. The citations for student projects and bibliographies are a cumulative record of work completed since the inception of the Center in 1978.

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Letter of Introduction

On behalf of the Palo Alto Veterans Administration Medical Center, we invite you to review the progress of the Rehabilitation Research and Development (RR&D) Center. As you will see, the RR&D Center is dedicated to bringing science and technology to bear on the problems faced by physically impaired veterans in their pursuit of living independence.

This is a complex challenge, and the RR&D Center has responded with a balanced program of research, design, development, and evaluation. The Center does not provide patient-specific clinical services. However, investigators pay close attention to patient concerns in formulating objectives, and they involve patients in the evaluation of new devices and technologies.

We welcome your examination of the RR&D Center—its programs, its people, and its facilities. We hope that this report will not only inform you about the state of the art in rehabilitation research, but also introduce you to a dedicated team of individuals who are working as a team to realize the human benefits of technology.

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THE CENTER

BACKGROUND In 1976, Dr. Thomas Newcomb, Assistant Chief Medical Director of Research and Development for the Veterans Administration (VA), recruited Dr. Vernon Nickel, who was then director of the Rancho Los Amigos Department of Rehabilitation, to establish the Rehabilitation Research and Development Service for the VA. The Service was to be explicitly devoted to the application of engineering science and technology in rehabilitation, and one of its key concepts was the establishment of centers of excellence where engineering faculty and students from major universities could collaborate with the existing VA medical research community on rehabilitation projects.

The Palo Alto Rehabilitation Research and Development (RR&D) Center was the second center to be established, and it is one of three such centers administered by Dr. Margaret Giannini since 1982 as part of the national Rehabilitation R&D Service. It began in May, 1978, under the directorship of Larry Leifer, Ph.D., with two research and development projects, five graduate student projects, and an annual budget of $178,000. Today the RR&D Center has a 6400-square-foot office and laboratory building on the Palo Alto VA Medical Center campus, an annual budget of over $2 million, and a staff of over 70 full- and part-time individuals working on some 50 projects that cover a broad spectrum of state-of-the-art rehabilitation research.

The RR&D Center is staffed by a vigorous group of individuals dedicated to building a new intellectual foundation for the use of engineering science and technology in rehabilitation. Currently there are four program areas—orthopaedic biomechanics, neuromuscular systems, human-machine integration, and technology transfer—each led by an engineer and a physician who have turned their energies to the challenge of making rehabilitation a premiere academic discipline. Other staff are research scientists and biomedical engineers, recruited from outside the rehabilitation community, to introduce expertise in robotics, biomechanics, computer simulation, mechanical design, kinesiology, microprocessors, signal processing, linguistics, and artificial intelligence. Extensive collaboration takes place with other researchers in the VA, at Stanford University, around the United States, and internationally.

The RR&D Center's close proximity to other VA research centers on the Palo Alto VAMC campus has facilitated several investigative partnerships. These centers include the Neurology Service, the Spinal Cord Injury Center, the Western Blind Rehabilitation Center, the Physical Medicine and Rehabilitation Service, and the Geriatric Research Education and Clinical Center.

The RR&D Center enjoys a long standing and successful affiliation with the Stanford University Schools of Engineering and Medicine. Each of the program directors and medical directors holds a Stanford faculty appointment. The RR&D Center supports a large number of masters and doctoral research projects. Graduate and undergraduate students are routinely involved in the research program and student design projects. RR&D staff serve as instructors and lecturers at Stanford. One of the RR&D Center's expressed objectives is to expose engineering and medical students to the exciting challenges of a career in rehabilitation.

OBJECTIVES The RR&D Center is based on the premise that the creation and application of emerging technology is a key strategy for improving the independence and quality of life for disabled and infirm veterans. The Center's primary mission is to develop concepts, devices and techniques that support independence for these individuals. Mission performance will be measured by the number, timeliness, and quality of deliverables produced. Specific goals are the following:

(1) Perform research needed to gather and publish knowledge for the definition of concept, device, and technique design requirements. Goal

achievement will be measured by the number and quality of papers produced.

(2) Demonstrate concept, device, and technique feasibility. Goal achievement will be measured by the number and quality of laboratory models developed.

(3) Develop and clinically test concepts, devices, and techniques. Goal achievement will be measured by the number and quality of pre-production prototypes developed.

(4) Promote concepts, devices, and techniques. Goal achievement will be measured by the number and quality of invited workshops held and attended.

(5) Negotiate with the private sector for technical collaboration on concepts, devices and techniques. Goal achievement will be measured by the number and quality of agreements signed.

ORGANIZATION The Center is organized into four program areas: Orthopaedic Biomechanics, Neuromuscular Systems, Human-Machine Integration, and Technology Transfer[1]. Each of the four program areas operates autonomously under the guidance of its director and medical director. The Center director carries executive responsibility across all programs. The administration and technical support groups work to support each of the programs (see Figure 1). The directors of the Center and the programs, along with the administration and technical support supervisors, make up the Center's administrative committee (AdCom). Presently the AdCom is composed of the following individuals:

Larry Leifer, PhD	Director
Dennis Carter, PhD	Orthopaedic Biomechanics Program Director
John Csongradi, MD	Orthopaedic Biomechanics Program Medical Director
Felix Zajac, PhD	Neuromuscular Systems Program Director
Leslie Dorfman, MD	Neuromuscular Systems Program Medical Director
Larry Leifer, PhD	Human-machine Integration Program Director
Rod Hentz, MD	Human-Machine Integration Program Medical Director
Alvin H Sacks, PhD	Technology Transfer Program Director
– to be announced –	Technology Transfer Program Medical Director
Patricia McCarty, MA	Administration Supervisor
David Dungan	Technical Support Supervisor.

FUNDING RR&D Center funding comes primarily from the Veterans Administration (VA). VA Base funding supports basic facilities and supplies and the salaries of key personnel. It provides the foundation on which the individual projects are built. VA Merit Review funding provides specific support for all major projects, in the

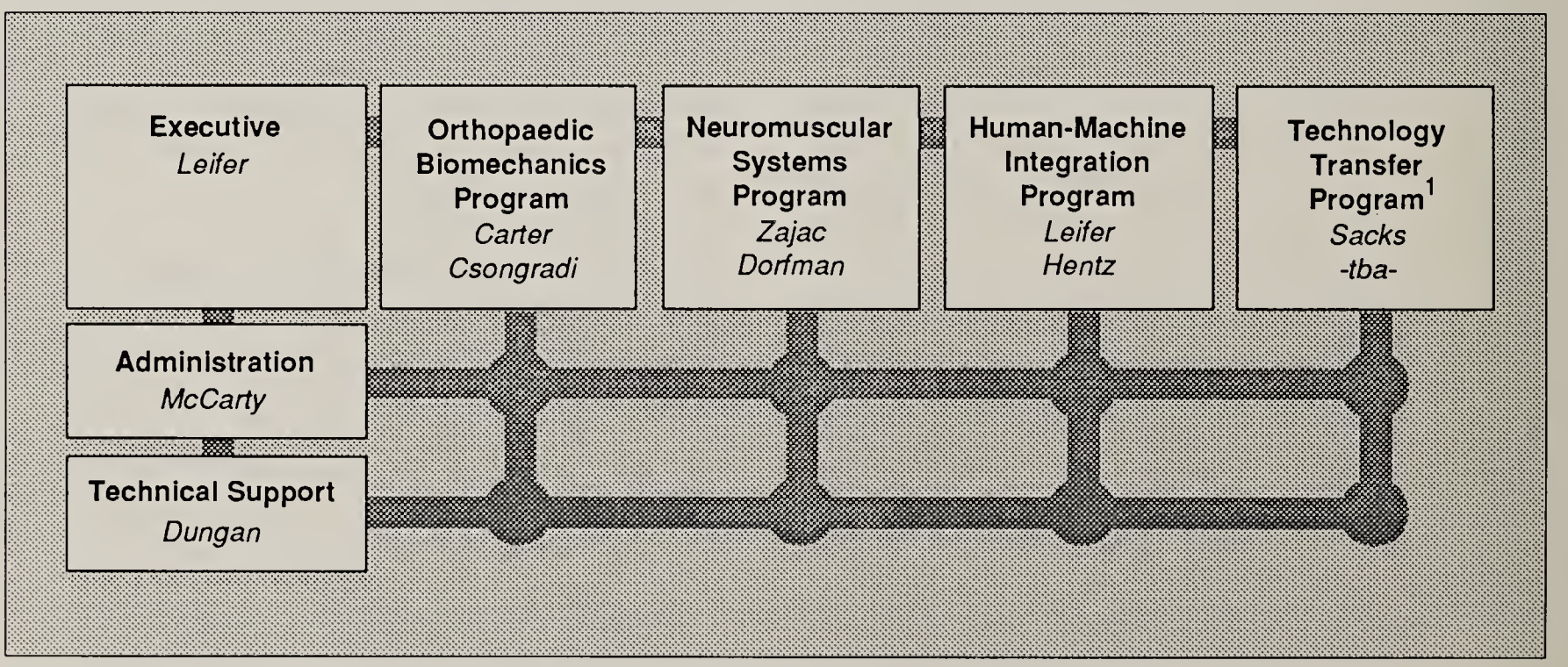
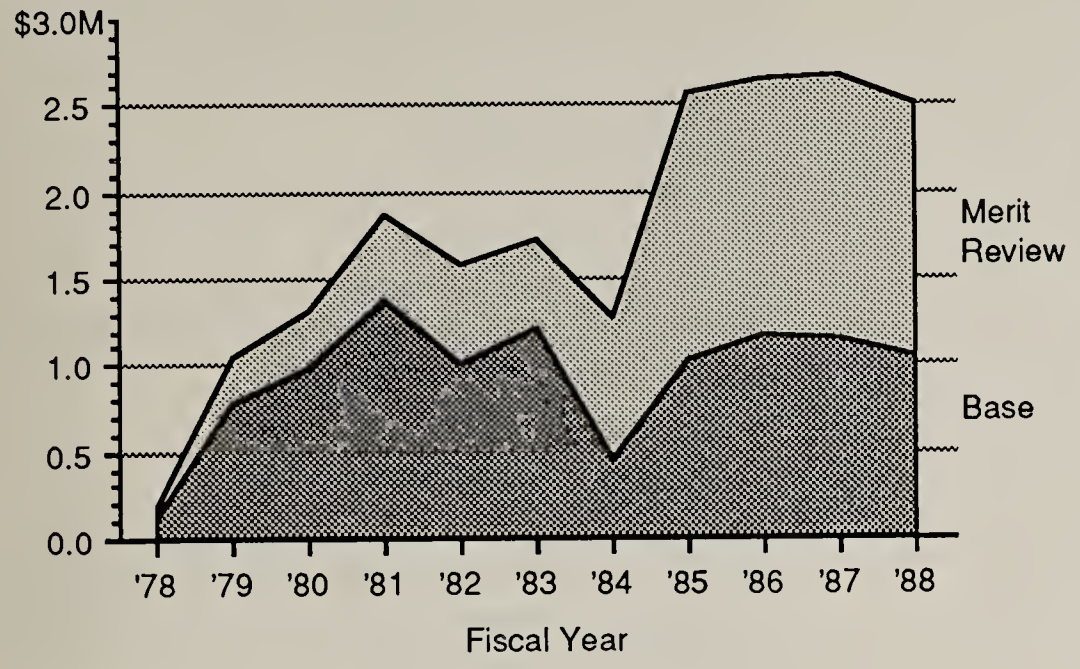


Figure 1. Internal organization of the Center: each program is under the executive responsibility of the Center director and is supported by the administration and technical support groups.

1. The Technology Transfer program was initiated January 1 1988.



Fiscal Year	Base	Merit Review	Total
'78	121	57	178
'79	771	267	1,038
'80	991	326	1,317
'81	1,376	492	1,868
'82	1,007	582	1,589
'83	1,203	513	1,716
'84	449	830	1,279
'85	1,030	1,545	2,575
'86	1,181	1,479	2,660
'87	1,150	1,512	2,662
'88	1,056	1,457	2,513

(Dollars, in thousands)

Figure 2. Funding history of RR&D Center, showing Base and Merit Review funding from VA sources.

form of grants awarded to the principal investigators. The graph above (Figure 2) shows the history of VA base and Merit Review funding for the Center since its inception in 1978. Investigators also attract funding from sources outside the Veterans Administration. This funding provides support for lines of investigation similar to those receiving VA funding and provides an important source of leverage for rehabilitation technology resources. Funded projects, both current and completed, are listed below.

CURRENT FUNDING ACTIVITY (FY88)

VA RR&D Merit Review

Design concepts for a porous ingrowth, prosthetic tibial component.
[Beaupré: $283,978 1985–88][1]

Stress analysis of internal fracture fixation of long bones.
[Beaupré: $204,080 1985–88]

Design stress analysis of porous ingrowth hip replacement.
[Carter: $305,700 1985–88]

Toward better methods of nerve repair and evaluation.
[Hentz: $683,021 1984–90]

Career development.
[Howard: $137,973 1987–89]

Development and evaluation of an advanced manipulation aid for the severely disabled.
[Leifer: $1,705,391 1981–88]

Application of the robotic aid for the severely disabled.
[Leifer, Perkash: $764,492 1985–90]

Treatment of physiological impotence.
[Perkash: $274,503 1986–89]

Career development.
[Pham: $137,973 1987–89]

Axonal regeneration in artificial nerve graft model.
[Rosen: $112,394 1987–89]

Dissemination of rehabilitation technologies.
[Sacks, Leifer: $205,282 1986–88]

Computer-aided visual communication for severely impaired aphasics.
[Steele: $240,000 1986–88]

Establishing design/operational features for new portable blind reading aids.
[Steele, Goodrich: $203,600 1987–88]

Dataglove semi-automated hand function evaluation system.
[Wise: $87,084 1988–89]

Computer models for designing FES systems for paraplegic standing and walking.
[Zajac: $723,500 1986–1991]

VA Medical Merit Review

Automatic decomposition of the clinical electromyogram.
[McGill: $61,200 1985–88]

VA RR&D Pilot Study

An instructable robotic aid.
[Michalowski, Leifer: $33,000 1988]

1. Investigator: cumulative funding, years funded.

Acceleration monitoring of acute spinal injury patients.
[Sabelman: $14,700 1988–89][1]

Skin blood flow response to loading.
[Sacks: $23,160 1988]

Alter blood rheology in spinal cord injured.
[Sacks: $23,686 1988]

National Institutes of Health

Mechanical loading and biological response.
[Carter: $312,000 1986–88]

Intermuscular coordination of mammalian movement.
[Zajac: $1,539,443 1982–94]

Alfred P. Sloan Foundation

Does neural-coupling of CNS output restrict motor coordination in the human?
[Zajac: $142,500 1987–88]

National Aeronautics and Space Administration

Development of a space-suit prehensor.
[Leifer: $184,000 1986–88]

VLSI spine robot.
[Leifer: $73,000 1987–88]

Conservation of design knowledge.
[Leifer: $199,000 1987–88]

Operational access to CAD knowledge bases.
[Leifer, Banks: $308,033 1987–88]

International Business Machines (IBM)

The cut-plane editor.
[Leifer: $56,000 1987–88]

COMPLETED PROJECTS

Development and evaluation of a downhill ski-sledding system for the disabled. [Axelson][2]

Olivocerebellar mechanism of motor coordination.
[Boylls, Zajac, Zomlefer]

External and internal stabilization of the disrupted cervical spine. [Csongradi, Perkash, Koogle]

Nerve bundle conduction velocity distributions: clinical research applications. [Cummins]

Personal information system. [Goodrich]

Development of a graphic braille display. [Goodrich, Jaffe]

Ultrasonic head control unit. [Jaffe]

Ultrasonic head control unit evaluation. [Jaffe]

Development and evaluation of wheelchair feedback controllers. [La]

Intelligent control-system design aid. [Leifer (IBM)]

Interactive motion and graphic simulator with real-time dynamics (IMAGES). [Leifer, Zomlefer, Goodrich]

A smart trigger for real-time neuroelectric spike classification. [McGill]

Seating systems for body support and prevention of tissue trauma. [Perkash]

Diagnosis- and treatment-compatible spinal injury patient stabilization and transport device. [Sabelman]

Para-bike. [Schwandt]

Para-bike evaluation. [Schwandt]

Sunburst tandem bicycle. [Schwandt]

Development of a life satisfaction scale applicable for people with severe disabilities. [Shindell, Goodrich]

Development of a camera for application in sensory aids for the blind. [Wood, Steele]

The spinal locomotion pattern generator in humans.
[Zomlefer]

Optimal biomechanical design/development of arm-powered mobility vehicles. [Zomlefer, Schwandt].

1. Investigator: cumulative funding, years funded. 2. Investigator.

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Publications Information

The Rehabilitation Research and Development Service Office of Technology Transfer publishes the *Journal of Rehabilitation Research and Development* quarterly in January (Winter), April (Spring), July (Summer), and October (Fall).

The annual *Rehabilitation R&D Progress Reports* of investigative research ongoing throughout the world is circulated in February.

In addition, periodic clinical and information supplements to the *Journal* focus on particular areas of interest to the rehabilitation community.

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COLLABORATIONS Individual staff members at the RR&D Center are currently collaborating with a variety of other institutions. Some of these interactions are formalized by contracts and co-authorships, while other important transactions take place on an informal one-on-one basis. In this area particularly, individual initiative is encouraged and supported.

VA Medical Center
Geriatric Research and Education Center
Neurology Service
Orthopaedic Surgery Service
Physical Medicine and Rehabilitation Service
Plastic and Reconstructive Surgery Service
Spinal Cord Injury Center
Western Blind Rehabilitation Center

Stanford University
Biology Department
Center for Design Research
Computer Science Department
Communication Department
Electrical Engineering Department
Institute for Mathematical Studies in the Social Sciences (IMSSS)
Linguistics Department
Mechanical Engineering Department
Neurology Department
Psychology Department
Sociology Department
Speech and Hearing Department
Structural Biology Department
Surgery Departments: Orthopaedic; Plastic and Reconstructive; and General

Bay Area Institutions
Center for Independent Living, Berkeley

National Aeronautics and Space Administration (NASA), Ames Research Center: Man-Machine Integration Branch; Project Technology Branch; Research Facilities and Instrumentation Division
Palo Alto Foundation for the Handicapped
Palo Alto Senior Citizens Foundation
Rehabilitation Engineering Center (REC), Children's Hospital at Stanford (CHS)
Schlumberger, Stanford Park Advanced Research (SPAR)
Sensory Aids Foundation, Palo Alto
Smith-Kettlewell Eye Research Institute, San Francisco
Spinal Cord Injury Center, Santa Clara Valley Medical Center, San Jose
Telesensory Systems Incorporated, Mountain View
University of California, Berkeley: Mechanical Engineering Department; School of Optometry
Xerox, Palo Alto Research Center (PARC)

Other Institutions

American Association of Retired Persons, Washington, DC
American Foundation for the Blind, New York, NY
Community Resources for Independence, Santa Rosa, CA
Lehigh University
Paralyzed Veterans of America
Syracuse University
University of California, Davis: Mechanical Engineering Department
University of Delft, The Netherlands
University of Maryland: Electrical Engineering Department
University of Nijmegen, The Netherlands Engineering Department.

REPORTS

ORTHOPAEDIC BIOMECHANICS PROGRAM

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Orthopaedic Biomechanics Program

The Orthopaedic Biomechanics Program conducts research and development with an emphasis ranging from basic research to applied implant design. We feel that better patient care and rehabilitation must come from strategies which are founded on a knowledge of fundamental physiological and biomechanical principles. Some of the basic research conducted includes investigations of:

(1) the role of mechanical stresses in the growth, development, and degeneration of the skeleton,
(2) the mechanical properties of bone,
(3) bone fracture healing and remodeling, and
(4) the relationships between *in vivo* bone stress and bone physiology.

Knowledge gained in these studies is applied by our group and other researchers for patient diagnosis and prognosis. It also provides design criteria for orthopaedic implants. For example, basic research has developed mathematical relationships for cancellous bone strength and stiffness as a function of bone apparent density. These relationships are now being used as guidelines in developing new CT scan techniques for assessing bone strength in osteoporotic patients. The relationships are also used in computer simulations of total joint replacements by ourselves and other researchers who are evaluating various design parameters.

In our applied work, we are studying orthopaedic implants such as total joint replacements, fracture plates, and spinal stabilization techniques. Our philosophy is generally to investigate and evaluate implant designs from a generic perspective. That is, we try to identify design parameters which are distinctive and evaluate various design options. The emphasis is not necessarily to develop and champion a specific device but rather to provide a framework in which prosthesis design should proceed. The dissemination of the results of this type of work influences the way in which others in the orthopaedic community and industry approach implant design and, ultimately, patient treatment and rehabilitation.

Gary S. Beaupré, PhD
Dennis R. Carter, PhD
John J. Csongradi, MS, MD
Tracy E. Orr, ME

Stress Analysis of Internal Fracture Fixation of Long Bones

PROBLEM Internal plate fixation of fractured long-bones is a standard procedure for treating fractures which would be unstable if treated conservatively, (*e.g.*, splinted or casted). A possible complication resulting from internal fixation is refracture of the bone after the plate is removed. Clinical studies have shown refracture rates to be as high as 20 to 25%.

SIGNIFICANCE Internal fixation is frequently used on the long-bones of both the lower (tibia) and upper (humerus, ulna, and radius) extremities. In 1983, internal fixation was the most frequent operation performed by orthopaedic surgeons in the United States. In 1979 it is estimated that the cost to society from arm and leg fractures was in excess of 2.5 billion dollars.

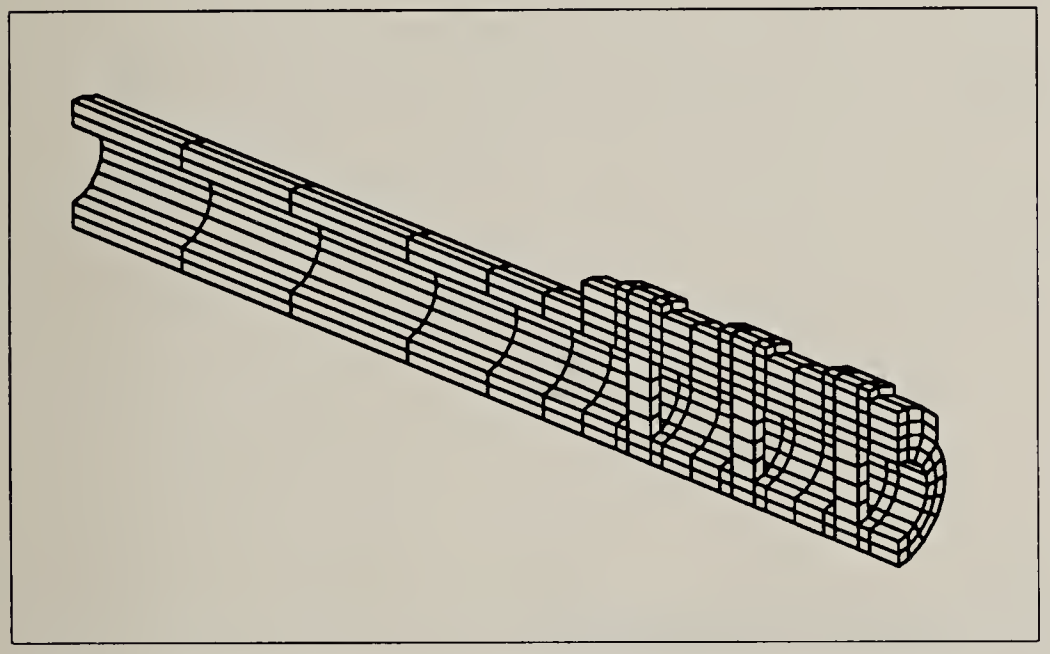

Figure 1. Finite element model of a plated long-bone (one quarter shown).

Refracture rates for the radius and ulna of 10 to 20% can be directly interpreted in terms of longer healing times, with an associated loss of human productivity and increased medical costs for reoperations and prolonged physician treatment.

BACKGROUND Although both damage to the blood supply and mechanical stress shielding have been implicated as contributing factors leading to refracture, no studies have assessed mechanical stress shielding using realistic mathematical models. All studies to date have assumed that no motion or slip occurs between the plate and the bone. However, numerous *in vitro* tests have shown that slipping between plate and bone occurs to a significant degree. By utilizing a non-linear, mathematical model that permits slipping between plate and bone, we will be able to accurately determine the extent to which stress shielding is responsible for bone refracture.

HYPOTHESIS Refracture after plate removal is caused by a combination of vascular damage and mechanical stress shielding. The importance of stress shielding has been overemphasized in all previous mathematical models since earlier studies have not incorporated realistic interface conditions. With the inclusion of realistic interface conditions, the amount of stress shielding may be significantly different than was previously thought. This may have significant impact on future plate design and on current plate application techniques.

APPROACH Using a non-linear finite element model (see Figure 1), we are capable of simulating slipping motion between the fixation plate and the fractured bone. Frictional contact elements are used to model the interface between the plate and bone and between the underside of the screw heads and the plate. The number of screws, screw tightness, plate geometry, and plate material have been addressed.

STATUS An idealized plated bone model has been developed and analyzed for five possible *in vivo* loading conditions. The degree of mechanical stress shielding is shown to be intimately related to how tightly the screws are applied. Loose screws produce minimal stress shielding, tighter screws produce more stress shielding. The use of tapered plates or shortened outer screws also reduces stress shielding. The results of the present study suggest that previous predictions of stress shielding may

be grossly in error. Iterative finite element algorithms are now being utilized to predict the extent of bone remodeling caused by plate application. Changes in bone density as a function of load type and load magnitude will be determined.

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SUPPORT

VA RR&D Merit Review (1985-present)
RR&D Core Resources

Gary S. Beaupré, PhD
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Development of a Mathematical Model of Fracture Healing

PROBLEM The healing of a fractured long-bone proceeds by stages of tissue differentiation in the various regions of the fracture callus. Once ossified, the callus then remodels and resorbs until the original form of the bone is restored. Two important factors that guide this process are vascularity (blood supply) and mechanical stimulus. A role played by mechanical stimulus was first postulated nearly a century ago, however a definitive model has never been adequately developed.

SIGNIFICANCE In 1984, fractures accounted for more than 2.3 million days of inpatient hospital care. Including hospital costs and disability days, fractures represent a total cost of more than 2.5 billion dollars per year. Because of this tremendous cost to society, much attention has been given to the development of various internal and external fixation devices for the treatment of fractured bones. The development of a mathematical model to quantify how a bone heals in the presence of different stress states and how the mechanical properties change accordingly will offer key insights into the design of these fracture fixation devices. In addition, a better understanding of fracture biomechanics should provide better clinical guidelines for treatment modalities of both normal and pathological healing situations.

BACKGROUND To date, there have been numerous histological and morphological studies on the healing process of fractured bones. The healing process has been categorized into four basic phases: (1) initial reformation of the vascular system with formation of soft callus tissue, (2) formation of cartilaginous callus, (3) formation of bone tissue, and (4) remodeling of bone tissue. These sequential phases stabilize and progressively stiffen and strengthen the healing bone.

There is some data available on the mechanical properties of the tissues involved, but no models exist which can describe or predict this healing process.

HYPOTHESIS The transition from the initial phases of a fractured bone to its original (reconstructed) form is influenced by the local state of stress and strain. In particular, the sequence of events from the cartilaginous stage to the formation of bone tissue is accelerated by intermittent or cyclic shear stresses and inhibited or prevented by intermittent hydrostatic compressive stresses.

APPROACH The finite element method is being used to create a mathematical model of a fractured long-bone.

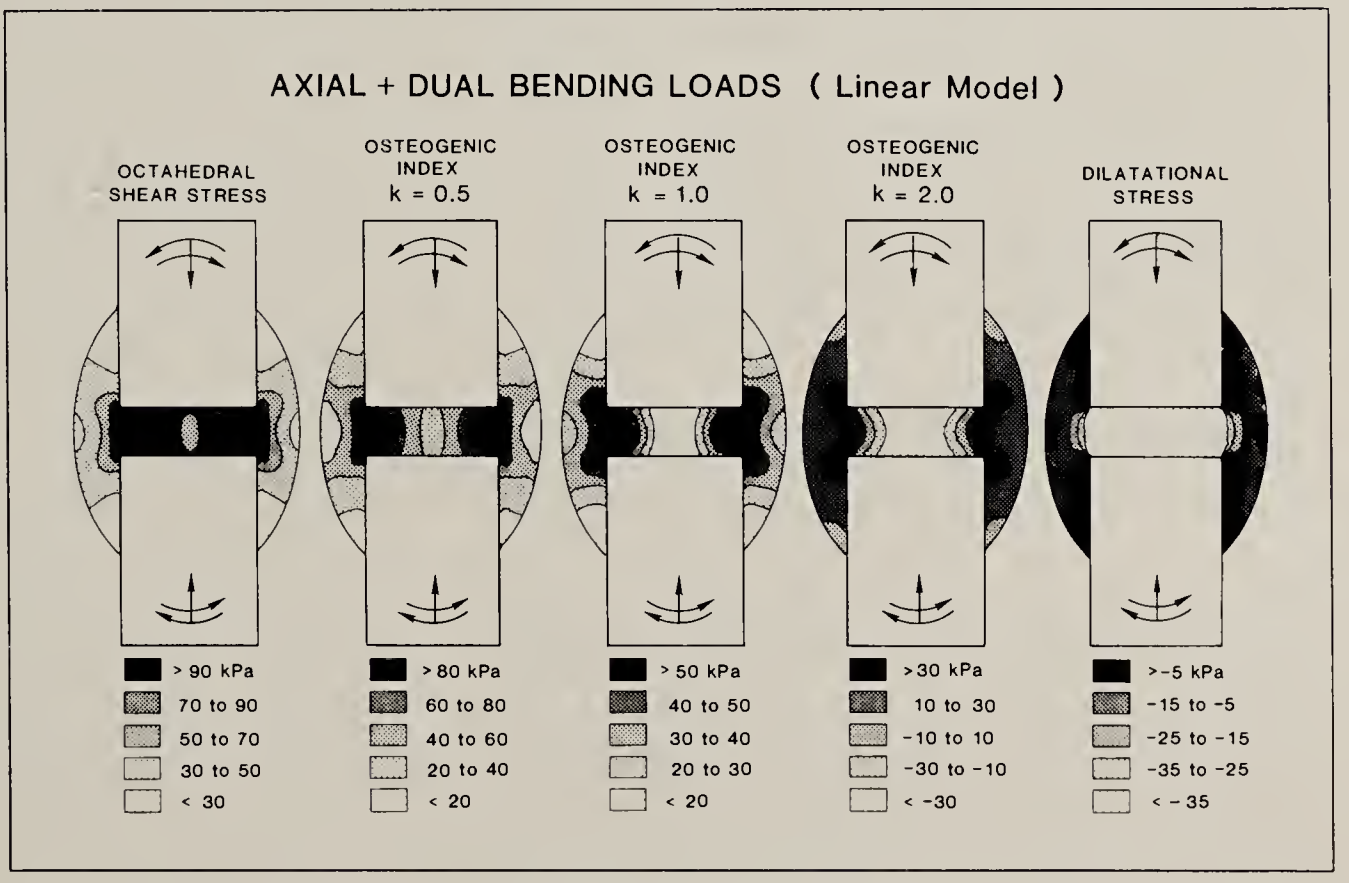

Figure 1. Contours of shear stress, osteogenic index, and hydrostatic stress for the finite element model with an axial load and two bending load cycles.

The idealized bone is based upon the mid-shaft geometry of the human femur. The appropriate loading and boundary conditions are obtained from previous studies using: (1) load-sensing implants and prostheses, (2) *in vitro* experiments, and (3) static and dynamic mathematical models of lower limb forces. An "osteogenic index" is used to provide a measure of the tendency of the healing tissues to differentiate into bone, fibrous tissue, or cartilage. This procedure will permit the temporal and geometric pattern of healing to be both predicted and followed.

STATUS Two-dimensional finite element models of a femoral mid-shaft osteotomy with various callus geometries have been developed. Results from these models (Figure 1) indicate that an osteogenic index of 2.0 or greater predicts healing patterns which agree with observations from both clinical and experimental studies. In Figure 1 darker areas correspond to regions where bone is predicted. Three-dimensional models that will permit additional loading modes (*e.g.*, torsion) are presently under development.

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SUPPORT

VA RR&D Merit Review (1985-present)
RR&D Core Resources

Gary S. Beaupré, PhD
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David J. Schurman, MD[1]

Bone Remodeling Around Porous Coated Tibial Components

PROBLEM In 1976 it is estimated that 40,000 total knee replacements were performed in the United States alone. With improvements in designs and techniques, it can only be estimated that many more replacements are being performed today. The rate of long-term success of these joint replacements, especially in young, active patients, is surprisingly low. The most frequent cause of mechanical failure is tibial component loosening.

It is now being recognized that biologic (bony-ingrowth) fixation of artificial joint components is one of the most challenging and potentially rewarding areas of research in orthopaedic surgery today. In spite of this, there is a paucity of studies that carefully and critically assess various cementless prosthetic designs in a quantitative manner. Our goals are to evaluate present tibial component designs and to make modifications that will result in new designs that have improved expected lifetimes.

SIGNIFICANCE Within two years (1990) it is estimated that more than half of all American men over the age of 65 will be veterans. During the next ten years, the total number of veterans over the age of 65 is expected to increase from the current 5.3 million to 8.9 million. Given that the majority of patients receiving total joint replacements are over the age of 65, it is clear that the veteran population will be a principal beneficiary of advancements in total joint replacement technology.

BACKGROUND Finite Element (FE) analysis has been widely used to study the design of prosthetic joints. Traditionally the main focus of such studies has been the distribution of internal stresses within a specific joint. While this continues to be true, the recent development of iterative remodeling programs now permits not only determination of stresses, but also the prediction of resulting changes in bone density.

HYPOTHESIS It is believed that the optimum prosthetic design is one in which the internal bone stresses are distributed similarly to those in the non-prosthetic joint. When such designs are used, extensive bone remodeling can be avoided, resulting in improved expected lifetimes.

APPROACH Both two- and three-dimensional FE models of the proximal tibia will be generated. These models will be based on actual bone geometry as determined from measurements of cadaver tibiae. The results of the anatomic or non-prosthetic tibia models will be compared with a number of different prosthetic designs. Several types of finite element models will be studied using two- and three-dimensional iterative finite element models.

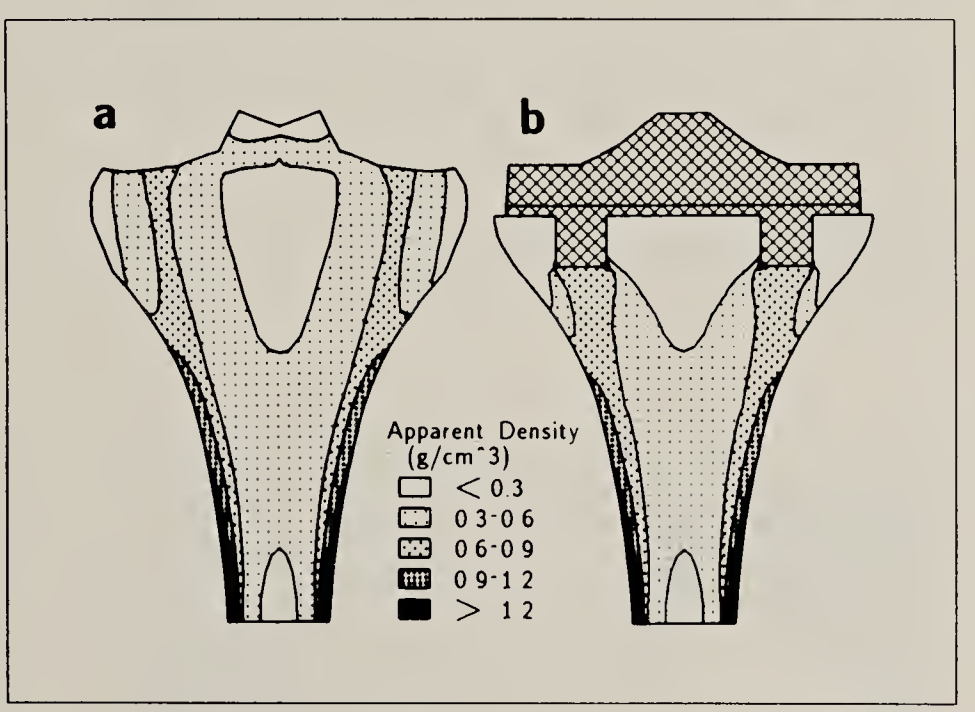

Figure 1. Results from two-dimensional remodeling analyses of the natural (left) and prosthetic tibia models (right).

STATUS Iterative remodeling analyses have been performed on two-dimensional models of the proximal tibia. Models of both the natural and prosthetic tibia have been analyzed. Results from the natural tibia model predict a density distribution (Figure 1a) that compares very favorably with anatomic observations. Results from the remodeling analyses on the prosthetic tibia model confirm the fact that large pegs lead to proximal bone resorption

1. Stanford University

and bone hypertrophy near the ends of the pegs (Figure 1b).

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SUPPORT

VA RR&D Merit Review (1985-present)
RR&D Core Resources

Nicholas Giori, BS
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Dennis R. Carter, PhD

Shear Stability of Fixation Pegs for Joint Replacements

PROBLEM Total joint replacement is becoming an increasingly common surgical procedure to relieve pain and restore motion in patients with advanced joint disease. Bony ingrowth fixation of these prostheses is a promising alternative to cement fixation in younger and more active patients. Problems often seen in prostheses intended for bony ingrowth include the growth of fibrous tissue, rather than bone, into the porous coating of the prosthesis.

SIGNIFICANCE For the year 1979 it is estimated that 70,000 hips were replaced in the United States at an average cost of $9500 per hip [1]. In 1983, the estimated number of hip replacements had increased to approximately 100,000. Projections based on these figures would indicate that more than 120,000 hip replacements will be performed in 1988. Accounting for inflation, the average cost per hip in 1988 approaches $20,000. This represents a cost to society of 2.4 billion dollars. With the addition of knee replacements this figure increases to more than 3.5 billion dollars per year. Given these costs, improvements in total joint technology take on a tremendous significance.

BACKGROUND Joint replacement prostheses are most commonly attached to bone using cement as a grouting agent. Studies raising questions concerning the long term stability of cemented prostheses have focused attention on a new technique for prosthetic attachment called bony ingrowth fixation. Prostheses using this technology are specifically designed for fixation without the use of cement.

One requirement for good bony ingrowth fixation is the need to minimize shearing motion at the bone-prosthesis interface. Fixation pegs play a key role in restricting this shearing motion. The purpose of this study is to examine the effects of peg geometry, size, and quantity on the shear stability of a typical bone-prosthesis interface.

HYPOTHESIS In prostheses to be fixed by bony ingrowth, stresses at the bone-prosthesis interface play an important role in the eventual success or failure of the implant. Failure to achieve good fixation of a prosthesis may be due to excessive shearing motion between prosthesis and bone.

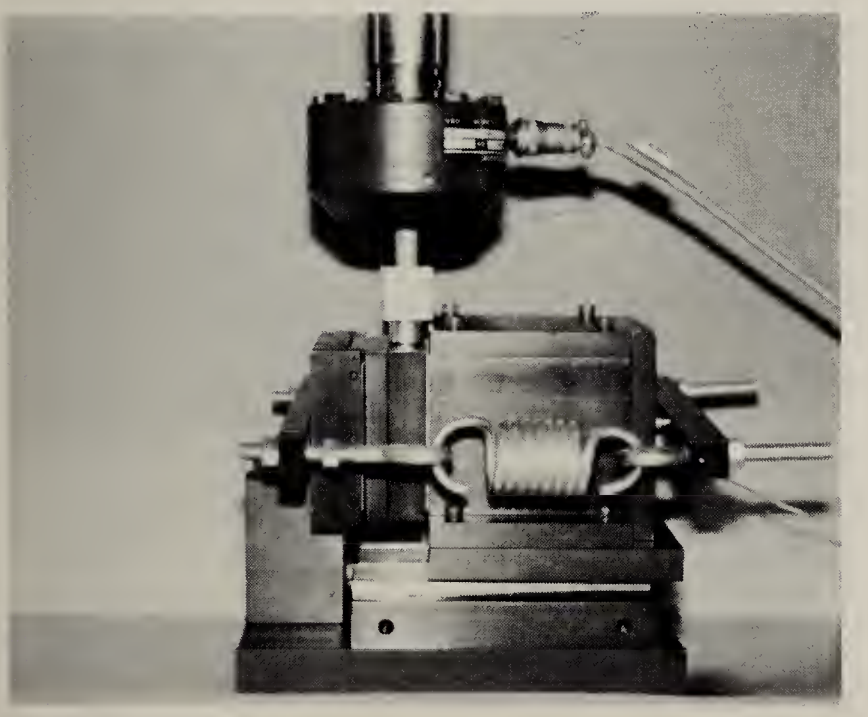

Figure 1. Testing apparatus.

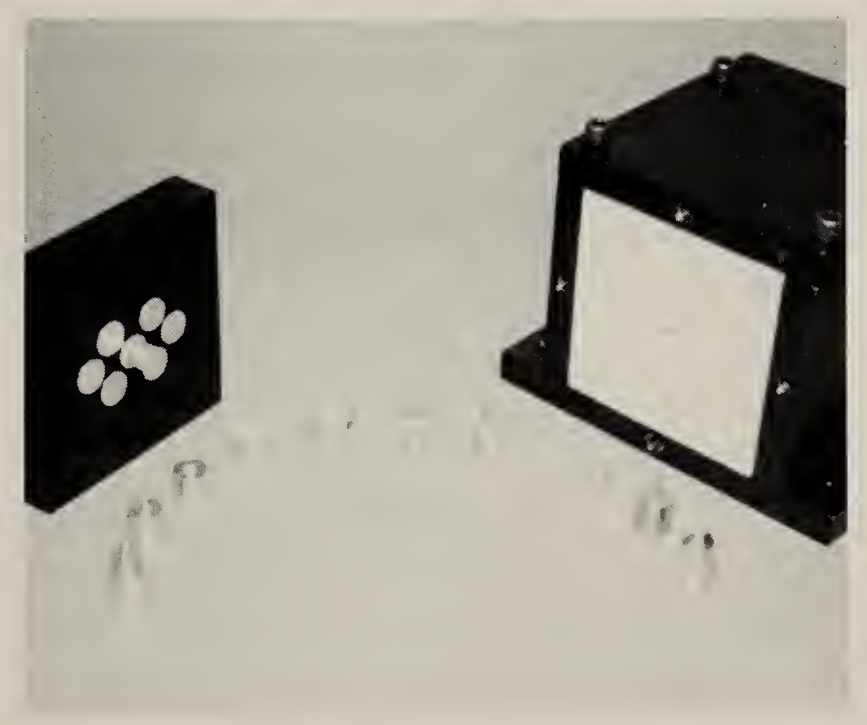

Figure 2. Peg design.

The shear stability of a prosthesis is a function of the geometry, size, and quantity of fixation pegs used. Understanding this relationship may result in recommendations regarding future prosthesis designs.

APPROACH Using a specially configured Materials Testing Systems (MTS) machine and a urethane foam with gross material properties similar to trabecular bone, we are able to generate shear at an interface similar to the bone-prosthesis interface. Pegs analogous to fixation pegs of prostheses can be tested to indicate the shear stability that they offer to the interface. A series of tests involving fixation pegs of various geometries, sizes, and numbers may lead to conclusions concerning optimal fixation peg design for resistance to shear forces between a prosthesis and bone.

STATUS A testing apparatus (see Figure 1) was designed and built which converts the axial loading of an MTS machine to the desired shear loading configuration. A 25–lb/ft^3 density urethane foam has been tested and found to have gross material properties similar to the trabecular bone which supports most joint replacement prostheses. Tests conducted with a representative variety of fixation pegs (see Figure 2) inserted into this foam indicate that pegs with a lower volume/projected shear area ratio have a higher shear strength/projected shear area ratio. Additional tests in cadaver bones are now underway to verify that the foam data are representative of tests in actual bones.

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SUPPORT

VA RR&D Merit Review (1986-present)
RR&D Core Resources

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Design Analysis of Porous Ingrowth Hip Replacement

PROBLEM Cementless fixation of artificial joint components is one of the most potentially rewarding areas of research in orthopaedic research today. It is well recognized that loosening of joint components is the major clinical problem associated with young, active individuals. Much evidence suggests that loosening is either directly or indirectly related to the use of acrylic bone cement as a grouting agent to secure the implants in the bone. If total joint arthroplasty is to be improved and to be extended to younger, more active patients, it is likely that new prosthetic designs which incorporate bone-ingrowth technology will play a major role.

SIGNIFICANCE Ingrowth of the bone into the surface of the implant will result in a very firm fixation and often a continuous, intimate interface that is efficient for stress transfer. With current prosthetic designs, the stress fields in the surrounding bone tissue can be radically changed from those in the normal skeleton. In animal studies, this condition has led to severe remodeling eventually leading to implant failure. More advanced designs and a better understanding of bone remodeling are needed to avoid these failures and to take advantage of the potential long service life which the bony-ingrowth technique offers.

BACKGROUND In the United States, a great deal of experimental and clinical interest has been developed using porous material surfaces for direct bony ingrowth. To date, the clinical applications of bony-ingrowth surfaces have been restricted to traditional-looking, stemmed hip prostheses. Experimental work with canines, however, suggests that surface-replacement types of components may be feasible. Animal experiments have also demonstrated that it is possible to achieve excellent bone ingrowth fixation in the acetabular components of a total hip system.

HYPOTHESIS The ability to predict the response of cancellous bone to applied stresses is critical to the eval-

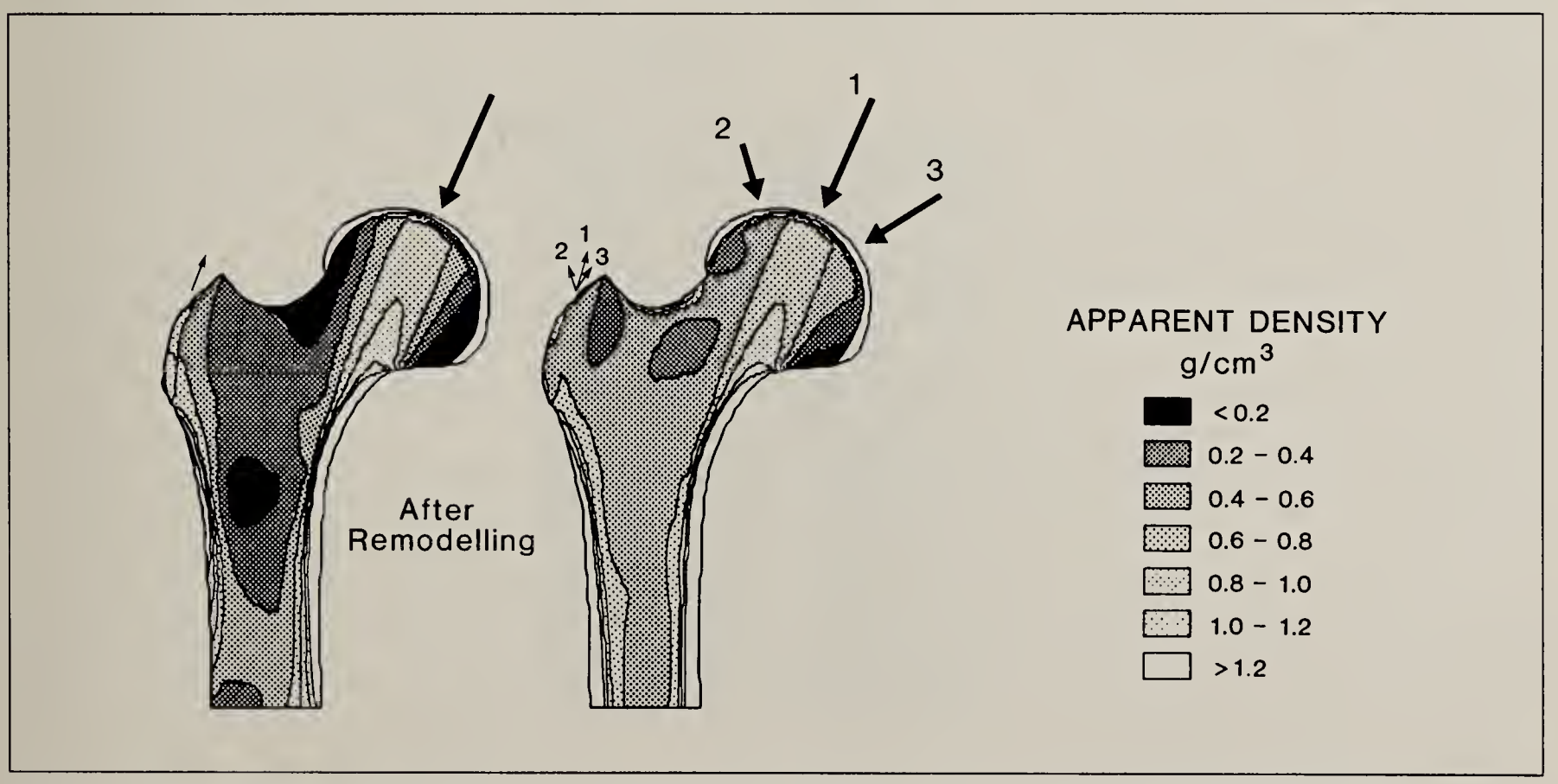

Figure 1. The predicted bone remodeling patterns for the normal femur using single and multiple-loading cases.

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uation of bony-ingrowth prosthetic designs. If the bone remodeling in response to implantation of a new prosthesis can be accurately predicted, the reliability of porous-ingrowth joint prostheses will be greatly improved and the time required for design and testing of new design concepts dramatically reduced.

APPROACH Using recently developed theories to predict the response of cancellous bone to multiple-load stress history, proposed prosthetic designs can be evaluated using finite element analysis. The results of these analyses can be validated by a sequence of simulations of known experimental results and by simulation of the normal distribution of bone density in the femur and pelvis.

Two-dimensional models of the proximal femur were generated based on anatomical specimens. Similar models with various bony-ingrowth implant components were also constructed. The remodeling theory predicts the distribution of bone density in the normal and prosthetic femur. This technique is an iterative approach in which the bone is initially a solid homogeneous femur. The results are compared with normal bone anatomy and with findings from clinical studies.

The development of these models requires detailed examination of boundary conditions, interface conditions, and loading conditions. For example, the interface between a newly implanted bony-ingrowth surface replacement and the underlying bone is neither perfectly sliding (frictionless) nor perfectly fixed (ingrowth). The simulation of this non-linear interface is an important part of predicting the success or failure of proposed component design.

STATUS We have applied the remodeling theory to several two-dimensional finite element models. The results have shown that the predicted natural bone density distributions for the proximal femur agree with previously documented observations. The remodeling routine predicted the development of a diaphyseal cortex and the dense compressive trabecular column through the head of the normal femur. The dense trabecular band corresponding to the arcuate system in the lateral-superior head was also formed.

We have investigated three femoral surface replacements thus far: a metal cup, a metal cup with a central peg, and a surface replacement that follows the shape of the epiphyseal plate. The implantation of these various prostheses was associated with a predicted remodeling pattern characteristic of the component under investigation. The remodeling patterns were consistent with the clinical and experimental findings of other investigations.

The remodeling theory is a promising step towards accurately predicting the biological events associated with initial ingrowth and subsequent bone remodeling. Our next step is to apply the theory to three-dimensional models so that it can be used to solve immediate design problems that have a direct clinical impact.

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SUPPORT

VA RR&D Merit Review (1985-present)
RR&D Core Resources

Robert C. Wood, MS
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Epiphyseal Replacement Prosthesis

PROBLEM Conventional total hip arthroplasty is a highly successful surgical procedure for treatment of severe arthristis of the hip. However, the incidence of mechanical failures in the form of femoral-component loosening and stem fracture has become an increasingly significant problem, especially in younger patients, and has renewed interest in conservative alternatives.

SIGNIFICANCE The theoretical benefits of total hip surface arthroplasty are the provision of a functional hip joint with a minimum removal of healthy bone. This would lead to a more natural stress distribution in the post-operative hip and would simplify re-operation if it were required.

BACKGROUND It was hoped that total hip surface replacement would be ideally suited for younger patients. Unfortunately, the failure rates of many types of hip surface replacements have been disappointingly high. The causes of failure have been attributed to stress concentration effects, stress shielding effects, micro-motions of the prosthesis, and vascular effects.

HYPOTHESIS One means of alleviating the stress shielding problem is to redesign the bone prosthesis interface such that the stress is transferred to the bone in a more natural manner. A naturally occurring surface which has the potential of being a good interface is the epiphyseal growth surface of the proximal femur (see Figure 1). Since the epiphyseal plate in young people is composed of cartilage, which is weak in shear relative to cancellous bone, the stress transmission across this interface is due primarily to normal pressure and tension. If the bone/prosthesis interface of a porous ingrowth surface replacement is designed to be similar in shape to the epiphyseal plate, a more normal transmission of stress to the bone may result (see Figure 2).

Figure 1. Cross-section of femoral head showing epiphyseal line and trabeculae structure.

Figure 2. Cross-section of femoral head and attached Epiphyseal Replacement Prosthesis.

APPROACH The Epiphyseal Replacement Prosthesis was designed in an effort to minimize load sharing and to provide for a direct transmission of force through the implant to the bone tissue. This series type of force transfer will tend to maintain the stress levels in the bone at a more normal physiological level and to reduce the magnitude of the shear stresses at the interface. A comparison of Figures 1 and 2 reveals that the bone/prosthesis interface of the Epiphyseal Replacement Prosthesis does indeed closely follow the line of the epiphyseal plate and is perpendicular to the main stress bearing column of compressive trabeculae, thus promoting series mechanical loading.

Finite element stress analyses (see Figure 3) were conducted on femoral heads before and after the implantation of an epiphyseal replacement prosthesis. The new epiphyseal replacement design resulted in stress distributions similar to those in the normal femoral head and in minimal shear stresses at the bone/prosthesis interface.

The Epiphyseal Replacement Prosthesis will be fixed to the femoral

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head through the use of bony ingrowth surfaces. A set of 1.5-mm diameter spikes are incorporated into the prosthesis at the bone/prosthesis interface to provide for firm initial fixation and to prevent micro-motions of the prosthesis. The spikes are of small enough diameter and length to avoid transmitting the load along their lengths to the bone. Simple instrumentation has been designed for implant installation.

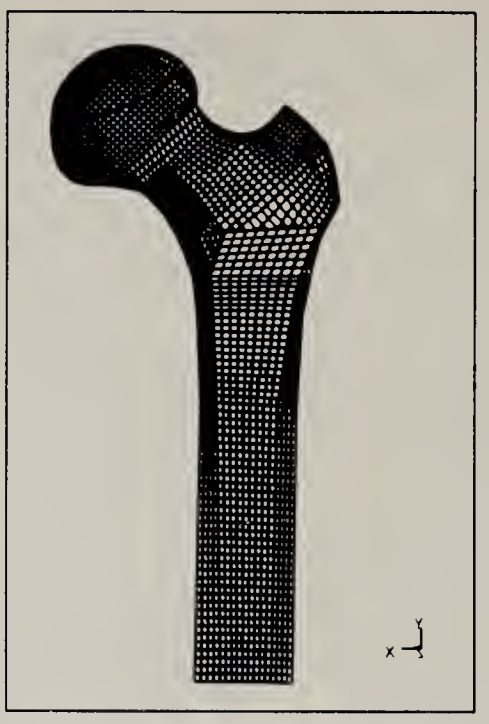

Figure 3. Finite element model of the femoral head.

STATUS Before implanting the epiphyseal total hip replacement prosthesis in humans, we propose to perform an animal study in which we will implant prototype prostheses in sheep. On the basis of the results of the animal project, we would then decide whether or not to implant these prostheses in human patients. The animal study will be an *in vivo* biological and clinical evaluation and should verify the theoretical model.

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SUPPORT

VA RR&D Merit Review (1986-present)
RR&D Core Resources

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David J. Schurman, MD[1]
Jay A. Mandell, MS
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Influence of Femoral Stem Collars on Stress Distribution in the Femur

PROBLEM Stresses in the femur after hip replacement have been studied for numerous implant designs. In addition, in several investigations, commercially available femoral components with collars have been compared to available collarless components. Nevertheless, no analysis that has yet been performed isolates the specific effects of the femoral stem collar for a range of collar geometries and under various means of femoral component fixation.

SIGNIFICANCE A better understanding of the effects on femoral stresses of using a flat collar, various conical collars, or no collar at all could facilitate decision-making in both the design and use of implants. Since various means of fixation are under consideration here, the results of this study will not be restricted to one particular means. The use of the"best" collar could reduce bone loss after hip replacement and reduce the probability of implant loosening.

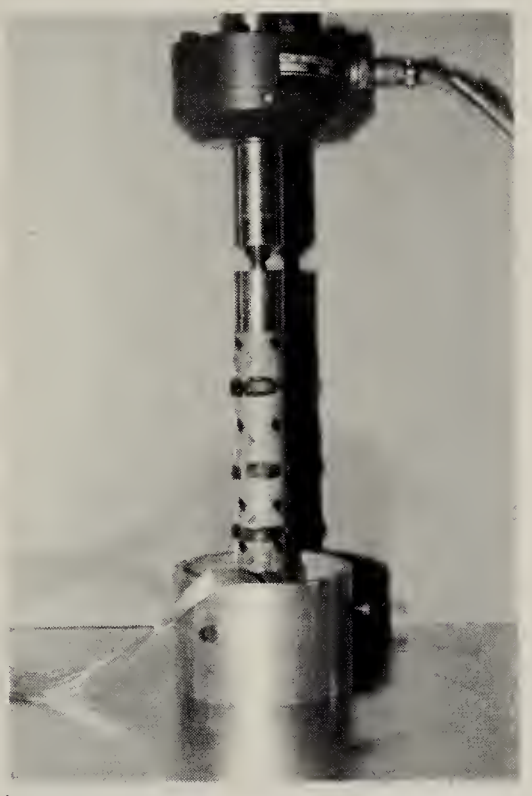

Figure 1. Strain-gaged assembly in mechanical test machine.

BACKGROUND The resorption of bone at the femoral neck after prosthesis implantation is generally agreed to be due to stress shielding of the bone. Bone loss further alters the distribution of stresses in the intact femur, and may lead to loosening of the prosthesis. Stress shielding is due to prosthesis geometry, the method of fixation, and the fact that prosthesis materials are typically six to twelve times as stiff as cortical bone. Collars have been added to some implant designs in order to increase the direct transmission of axial loads to the calcar femorale, thus providing a more natural transmission of load and reducing stress shielding. The question of which collar geometry can best accomplish this purpose has not yet been answered.

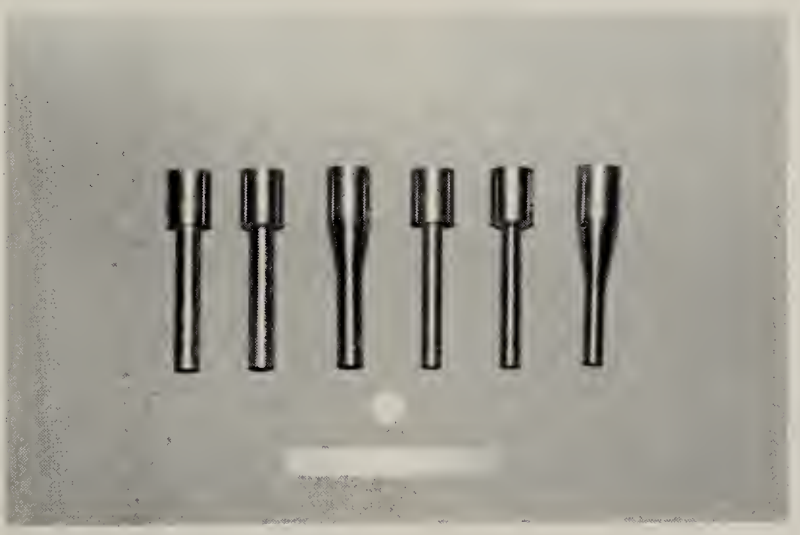

Figure 2. Prosthesis models.

HYPOTHESIS The function of the collar can best be studied using models of simplified shape in which only the collar geometry is varied. Most current prosthesis designs are collarless or utilize a flat collar; analytical results may demonstrate that a conical design is preferable.

APPROACH This study includes both finite element and experimental stress analysis. The prosthesis models include flat collar, conical collar, and collarless configurations. For each model, three methods of fixation are considered: cemented, close fit (no cement), and porous ingrowth. Load magnitudes and angles, based on the one-legged stance, are taken from the literature. For the experimental phase, the prostheses are made of steel, and bone is simulated using phenolic plastic tubes having axial stiffness similar to that of cortical bone. The experimental models are loaded in an electro-hydraulic mechanical testing machine.

STATUS The experimental models have been machined and mechanical tests performed on test specimens of the phenolic tubes. A computerized data acquisition system has been set up to record strain data. The first

1. Stanford University

phenolic tube has been strain-gaged with twenty-four strain gage rosettes and preliminary results have been obtained. A two-dimensional finite element model paralleling the experimental work is under development.

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SUPPORT

RR&D Core Resources

Dennis R. Carter, PhD
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Cumulative Material Damage in Bone Subjected to Creep and Fatigue Loading

PROBLEM Bone tissue subjected to mechanical loading will accumulate material damage that is dependent upon the type of loading, the magnitude of the loads, and the load duration. Relationships between the damage and the loading parameters are not well understood. The intent of this study is to assess the nature of material damage in bone tissue that is subjected to cyclic (fatigue), static (creep), and combined cyclic and static loading.

SIGNIFICANCE The bone remodeling response plays a role in all orthopaedic procedures. Joint replacement, implant surgery, and fracture fixation all depend upon bone remodeling for long term structural integrity. Diseases such as osteoarthritis affect bone remodeling and can lead to an alteration of bone structure or loss of bone mass. The biological processes at work in orthopaedics are influenced by mechanical demands and material state. Knowledge of the relationships between mechanical loading, material damage, and bone remodeling will contribute to clinical treatment in orthopaedics and may provide tools for the study of bone diseases.

BACKGROUND The mechanical forces imposed upon bones influence bone tissue growth and remodeling. These forces consist of combinations of cyclic and static loads. Each bone of the skeleton is not only subjected to different combinations of cyclic and static loads, but the distributions of these loads within the bone is also not uniform.

The bone remodeling stimulus is not known, but is either different at every point in the bone, or the bone tissue somehow filters the appropriate "adaptive" compo-

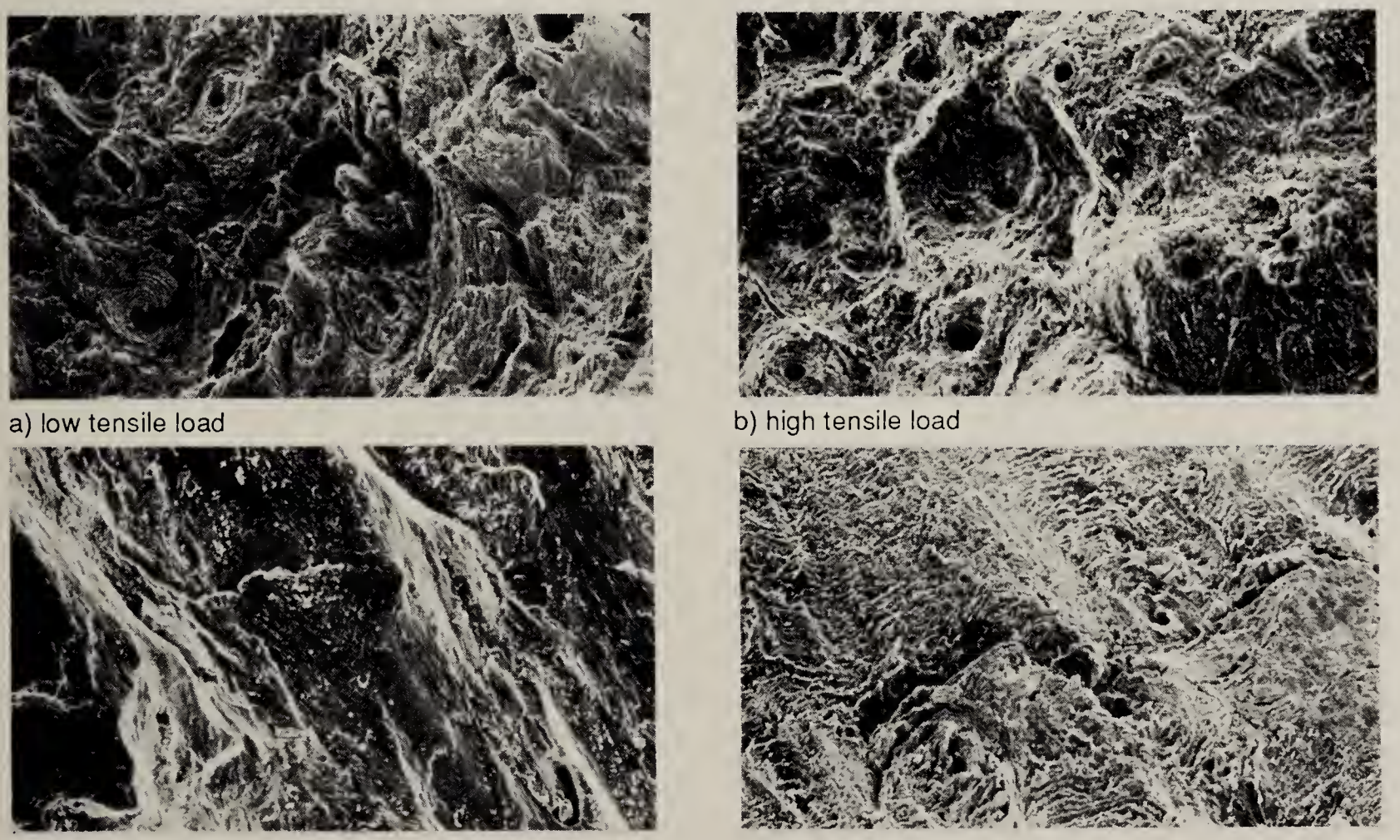

Figure 1. Scanning electron micrographs of four specimens tested under creep conditions.

nent from the loading history. Previous studies have shown differences in the nature of material damage created under different loading conditions. Since it is likely that bone tissue responds to physical damage at least in part, then characterization of material damage created by various combinations of creep and fatigue loading may provide insight into the bone remodeling response.

HYPOTHESIS Material damage created under a combined loading history can be considered as a superposition of the damage created by the load history components. The bone remodeling stimulus is influenced by one or more of the fundamental damage components.

APPROACH A complex loading history can be considered as a summation of simple load histories. Static loads in tension or compression, and cyclic loads in tension or compression are simple load histories. Material damage created by a static tensile load is different than damage created by a static compressive load. In the laboratory we apply these simple load histories to machined bone specimens until they fracture.

Observation of the fracture surfaces using a scanning electron microscope (SEM) provides evidence of damage created by the applied load. By documenting the damage created by a variety of simple load cases and using the principle of superposition, we can predict characteristics of bone fracture under more complicated loading histories.

STATUS Fracture surfaces of bone specimens tested under a variety of simple load cases have been observed and examples are shown in Figure 1. These scanning electron micrographs show surfaces of four specimens each tested under different creep conditions. The upper specimens were tested in tension and the lower specimens were tested in compression. The left specimens were tested at relatively low load, and the right specimens were tested at relatively high load.

Each specimen exhibits different fracture surface features, suggesting that the damage mechanisms for these loading cases are different. Results of mathematical analyses of the bone material behavior combined with the fracture surface studies have enabled us to separate some fundamental components of damage accumulation.

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SUPPORT

National Institutes of Health (1985-present)
RR&D Core Resources

Cheryl A. Pattin, MS
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Bone Fatigue and Creep Damage

PROBLEM The properties of human cortical bone *in vitro* change over the fatigue and creep life of a specimen due to the accumulation of damage. Changes in properties such as stiffness and energy dissipation per cycle (hysteresis) in fatigue need to be further examined to gain insight into the damage accumulation process culminating in fracture or remodeling *in vivo*.

SIGNIFICANCE Changes in bone mechanical properties due to creep and fatigue accumulation may stimulate the remodeling process. Property changes in bone occur gradually over the loading history and may therefore play a role in initiating remodeling well before bone fracture. The damage accumulation process may also occur very differently in pathological bone such as bone with osteoporosis or osteoarthritis. An understanding of damage accumulation and its effect on bone may provide important considerations for prosthesis design, physical therapy of injured bones, and treatment of bone diseases.

BACKGROUND Bone is subjected to a variety of cyclic (fatigue) and static (creep) loading *in vivo*. Changes in loading can lead to fatigue fractures, osteoporosis, or remodelling. The energy transferred to bone or the changes in bone material properties may stimulate the remodeling process. To understand the response of bone to complicated loading histories such as those encountered *in vivo*, modelling of bone mechanical response to fatigue and creep loading is important.

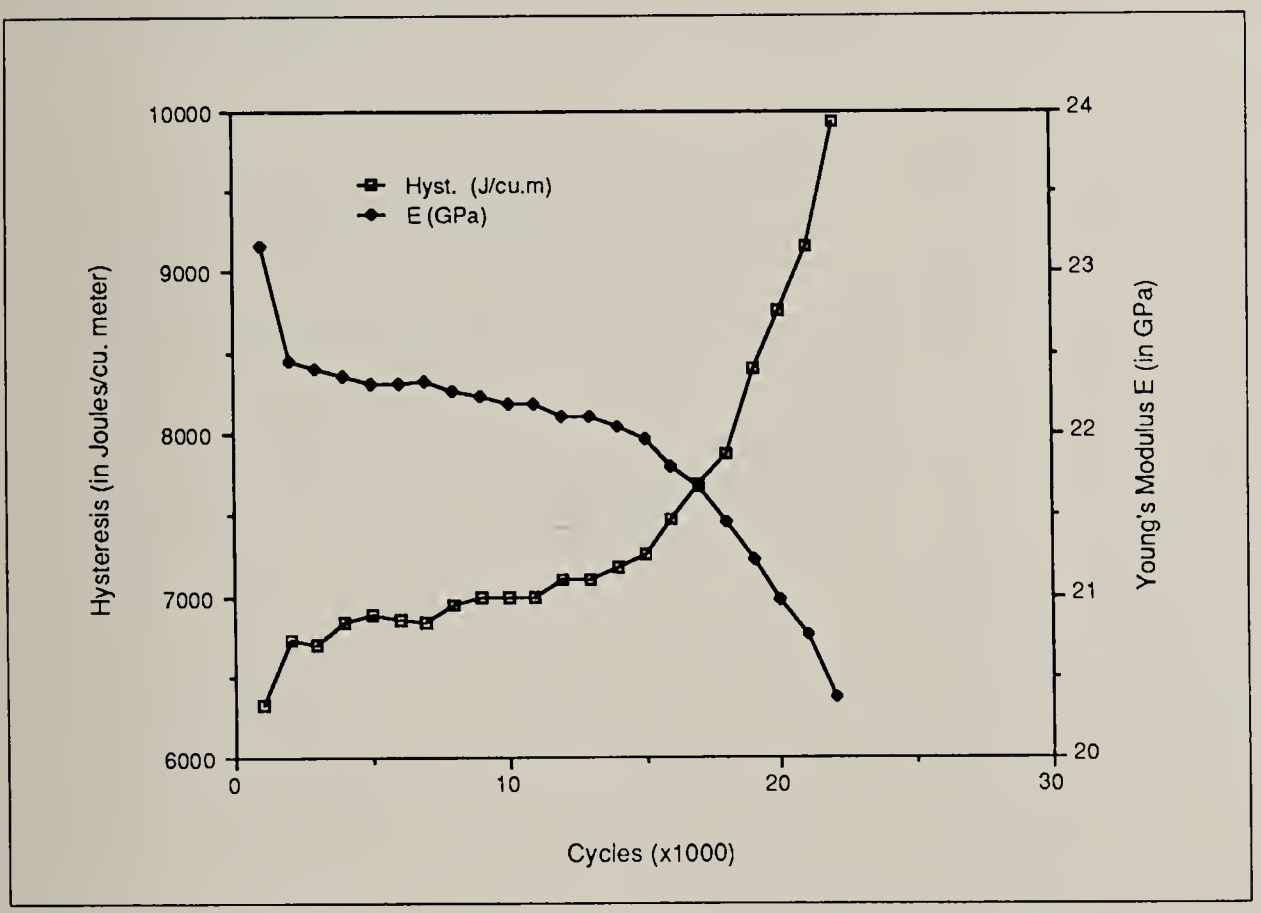

Figure 1. Variations of mechanical properties over fatigue life at 63 MPa.

HYPOTHESIS Damage accumulation due to mechanical loading of bone stimulates remodelling. This stimulation may come as the result of changes in energy dissipation, changes in bone material properties, or the formation of microcracks.

APPROACH The skeleton is normally subjected to complex loading histories that can be considered a summation of static (creep) and cyclic (fatigue) forces. In the laboratory, the creep and fatigue response of bone can be characterized by applying static or cyclic forces to machined bone specimens or to whole bones, and by observing how the material deforms or fractures. Bone tissue also behaves differently under various loading histories. The response to tensile loading is not the same as the response to compressive loading. Our approach is to study a variety of simple loading histories and then use the principle of superposition to predict the bone response to combined loads. When subjected to high loads, or to low

loads over a long period of time, bone will accumulate damage and eventually break. The nature of the accumulated damage is different depending on the type of load applied. The fracture surface may be viewed under a scanning electron microscope (SEM) to visually observe the damage leading to fracture. The damage accumulation process also results in changes in bone material properties and energy dissipation, as is the case for composite materials in general. By observing changes in these mechanical properties during fatigue and creep testing, the nature of the damage accumulation process may be more fully understood.

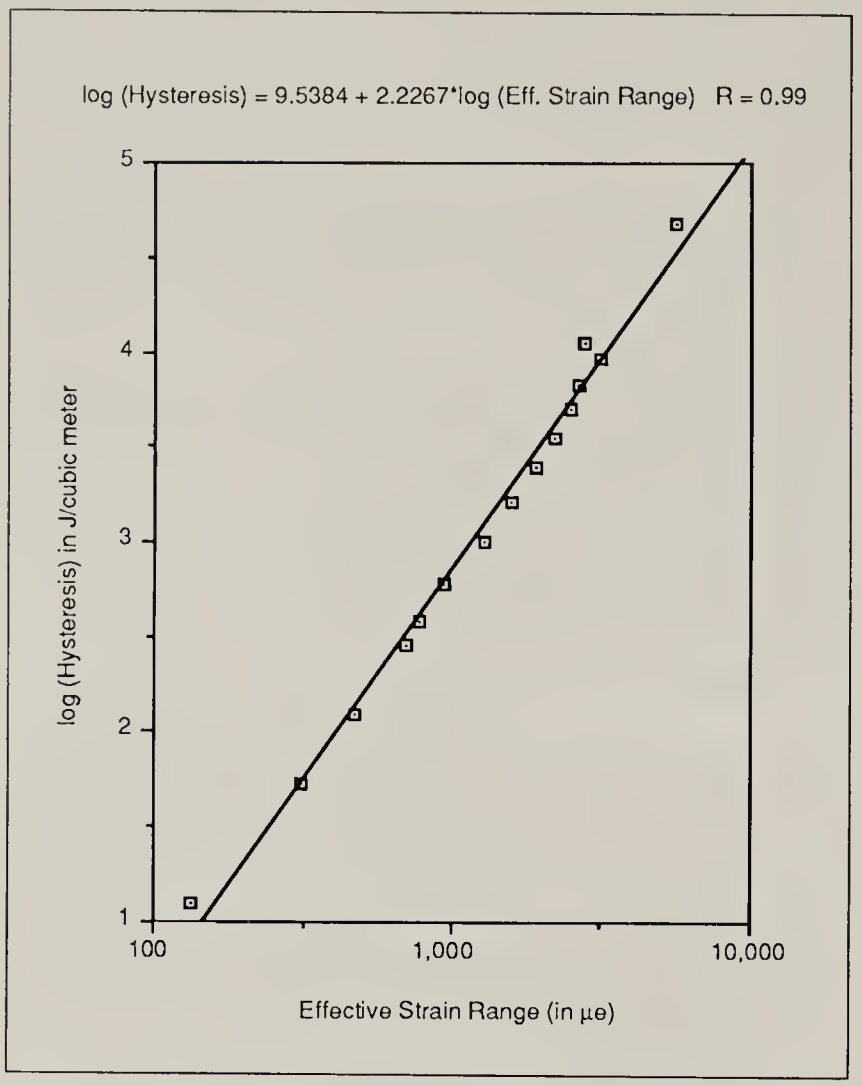

Figure 2. Power law relating hysteresis and effective strain.

Living bone must repair accumulated damage or it will lead to a fracture. Bone remodeling may be specific to the type of damage occurring in the material. Our studies are aimed at establishing relationships between the nature and extent of the damage incurred and the loading histories imposed.

STATUS Waisted cylinders of cortical bone were formed from human formora and subjected to various fatigue tests at body temperature (37 °C). Changes in stiffness and hysteresis (energy dissipated per cycle) were determined in tests at single stress levels, such as the test results from a zero-to-tension fatigue test performed at 63 MPa shown in Figure 1.

Some specimens were tested at a variety of different stress levels, and variations in the hysteresis were found to be slight after the first twenty-five cycles or so for loads below 60 MPa. The hysteresis at a given stress level was found to be related to the effective strain (stress range divided by the initial stiffness) by a power law of the form: log (Hysteresis) = log(A) + B × log (Effective Strain Range) where hysteresis is measured in Joules/cubic meter. For several specimens at various stress levels, the constants A and B were found to be log(A)=9.54 and B=2.23, with a correlation coefficient of 0.99. A graph of this relationship for the specimens tested is presented in Figure 2. These relationships can be combined with lifetime prediction relationships developed previously by Carter and Caler [1] to understand how lifetime energy dissipation is accumulated and related to damage. Further study will address creep damage accumulation and creep-fatigue damage accumulation under more complicated loading histories.

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SUPPORT

National Institutes of Health (1985-88)
RR&D Core Resources

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Christine Harter, PhD[2]
Mary L. Bouxsein, BS[2]

Exercise Intensity and Bone Mass in Young Women

PROBLEM Skeletal mass and bone density measurements of selected trabecular bone sites are often used to assess the condition of the skeletal system. The variety of body sizes and types makes the interpretation of these absolute measurements difficult. Attempts to normalize bone density measurements with respect to physical size have not been and can not be successful. Beyond body size and other hereditary influences, factors identified as regulating bone volume include activity level, exercise, sex, diet, race, and hormone levels.

Proper correlation between these variables and skeletal response is needed to identify the factors affecting bone maintenance and to guide clinicians in the development of programs to prevent, reverse, or slow the loss of bone with aging.

SIGNIFICANCE Starting at approximately the age of 25, skeletal mass begins a gradual, steady decline of 0.5

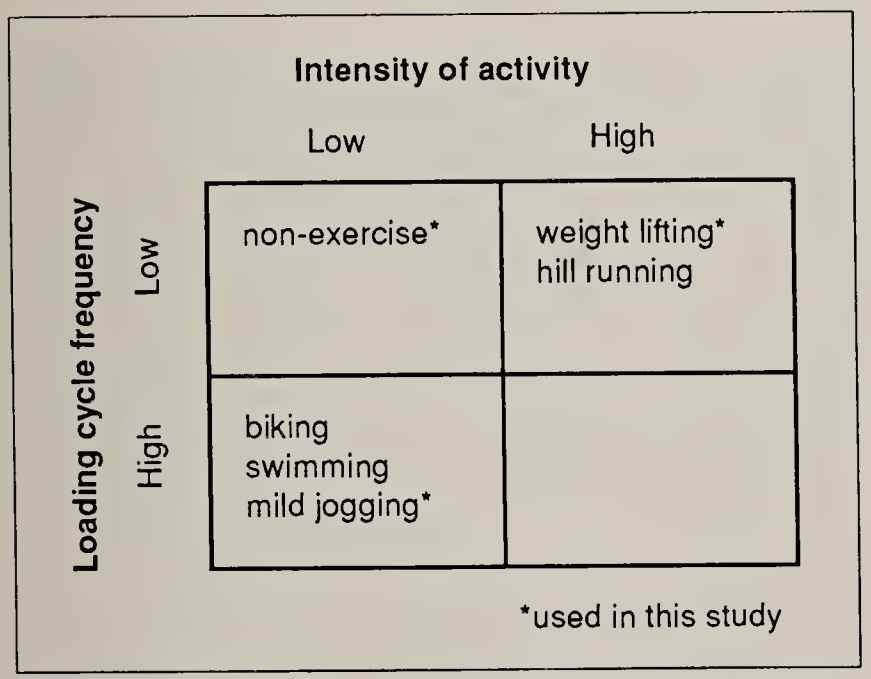

Figure 1. Exercise types: asterisk indicates those used in this study.

to 1.0 percent per year for women. This loss remains steady until approximately age 50 at which time loss of female hormone, estrogen, accelerates the loss of bone. In men, early bone loss also occurs, but at a substantially lower rate than women. Bone loss weakens the skeletal system and reduces its ability to withstand the imposed mechanical forces of daily living. Spontaneous fractures of load-bearing bones are common in osteoporotic individuals, defined as those who have lost enough bone to markedly increase their risk for fractures. Early detection and prevention of osteoporosis requires a quantitative understanding of the environmental factors which influence bone mass. We suggest that prevention may take the form of exercises tailored to promote and maintain high bone density throughout life.

BACKGROUND Clinical and experimental evidence suggests that for healthy young persons, activity level is the dominant regulator of bone mass. Athletic activities which involve significant increases in joint loads increase bone mass in the heavily loaded bones. The humerus of the playing arm of 84 world-class tennis players showed pronounced hypertrophy [3]. Cross country runners were found to have a 20 percent greater calcaneal density that a non-exercising control population [2].

On the opposing end of the loading spectrum, removal or reduction in the level of physical activity through immobilization or bed rest consistently results in severe bone resorption. Numerous bed rest studies have included exercise protocols to test the hypothesis that forces on the body regulate skeletal mass. None of these was successful in reducing the level of bone loss. Although this fact might cause some to question the role of exercise in the regulation of bone, we find no contradiction in the results and suggest the problem lies in misunderstanding what constitutes effective loading of the skeleton.

HYPOTHESIS Stress as a stimulus has been implicated in the regulation of bone morphology. The orientation of trabecular bone along principal stress directions has been verified recently by finite element models, and bone appears to concentrate in regions of high stress. Remodeling is a continuous process of skeletal destruction and renewal, occurring throughout life [5]. We hypothesize that bone in a state of near equilibrium must be a function of

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a daily remodeling stimulus rate, which is itself a function of the load history. Thus if the level of physical activity suddenly increases (decreases), the daily rate of applied stimulus increases (decreases). The body responds to this loading and tries to provide the bone tissue with a constant level of stimulation.

Since body weight, height, daily activity level, and exercise all contribute to the loading history, the daily remodeling stimulus becomes a fundamental variable for bone density normalization. Specifically, the daily remodeling stimulus may be a summation of external load factors created by daily activities. These daily activities may be considered as discrete events, each represented by frequency and intensity terms. We hypothesize that the intensity of activity is more important to bone density than the number of loading cycles [1, 6].

APPROACH To test the intensity versus frequency hypothesis an exercise study was designed. College-age, healthy women are recruited and assigned at random to three groups: weight training, running, or control. Weight training represents a high-force, low-repetition exercise, while running represents a low-force, high-repetition activity. Women placed in the weight training or running groups underwent regular, supervised exercise programs. The control group maintained their current activity level.

Total bone mineral and regional bone densities in several anatomic regions (feet, knees, hips, lower spine, shoulders) were measured by dual photon absorptiometry. Measurements were taken at entry and at regular intervals throughout the study. Average daily loading histories for each subject were determined from activity logs and exercise records kept by the subjects. The change in total and regional bone mineral mass was predicted from the daily stress history and compared with actual measurements. Also, the differences in theoretical predictions and experimental results was compared between groups.

STATUS A 5-month pilot study was completed. The results qualitatively confirmed the hypotheses relating exercise intensity and frequency to bone response [4]. At present approximately 70 women have been recruited and have been assigned to one of the three groups. Initial total bone mineral and regional bone densities have been determined for each subject. Each subject in the weight training or running group has begun a supervised exercise program, and all participants have completed daily activity and exercise records. The results of the study may have far-reaching clinical relevance in preventing bone loss and its associated complications.

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SUPPORT

National Institutes of Health (1985-present)
RR&D Core Resources

Marcy Wong, MS
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The Role of Mechanical Stresses in Degenerative Joint Disease

PROBLEM Symptoms of degenerative joint disease affect approximately 25% of women and 15% of men after the age of 60 [1]. The articular cartilage that covers all joint surfaces is normally smooth and well-lubricated and allows a gliding, almost frictionless articulation of the joint. In degenerative joint disease, however, the cartilage becomes fibrillated and soft, and the bony layer underneath the cartilage layer becomes prone to the formation of cysts at specific sites. These degenerative changes make normal movement painful. Degenerative joint disease most commonly afflicts weight-bearing joints such the hip and knee. However, all joints of the appendages and the spine are susceptible.

SIGNIFICANCE It is estimated that in 1987 over 120,000 artificial hip replacements were performed at an average individual cost of $20,000. The artificial prostheses are primarily implanted to treat severe degenerative joint disease. The goal of this study is to understand how the mechanical loading history on the joint may have a detrimental affect on the viability of the cartilage and bone tissues. Once this fundamental understanding is achieved, it may be possible to prescribe a stress history that could correct or prevent the disease.

BACKGROUND One of the most useful techniques for determining the stress distributions within a bone and on the contact surface of a joint is to generate a finite element computer model that reflects the geometry, material properties, and loading history of the bone or joint of interest. In recent years, Carter *et al.* [2] have used finite element models to investigate the specific mechanical stress states within cartilage which tend to accelerate the ossification of this tissue. Using a computer model of a hip joint, Carter *et al.* [3] were able to predict areas susceptible to initial degenerative changes. Similar techniques will be employed in a model predicting the formation of site-specific cystic lesions.

Figure 1. Cystic lesion occurring on the medial femoral condyle of a thoroughbred horse.

HYPOTHESIS The previous mathematical formulation used to predict the transformation of cartilage to bone was a simple linear relation between the shear stress and the dilatational stress. In this study, the theory will be extended into the non-linear regime in the hope of predicting the localized damage of tissue on the cartilage/bone interface, (*i.e.*, the beginning of a bone cyst).

APPROACH We have chosen to examine the relationship between loading environment and the pathology of cysts using the knee of a thoroughbred horse as a model. The horse was chosen because of the availability of specimens and the high frequency of these site-specific lesions. The specimens will be provided by the Department of Veterinary Anatomy, University of California at Davis. Two- and three-dimensional finite element computer models are being generated of this

joint, and we hope to be able to predict normal morphogenesis as well as degenerative changes that may occur under more severe loading.

STATUS Several stifle joints containing subchondral cystic lesions have been obtained. Work is being done in the finite element area to examine elements that can accurately model the high shear stresses between two materials of very different material properties.

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SUPPORT

RR&D Core Resources

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The Effect of Joint Immobilization on the Biochemistry and Morphology of Bone and Cartilage

PROBLEM Osteoarthrosis is a degenerative joint disease in which the articular cartilage degenerates and new bone forms in the subchrondral area of the joint bone. Caused by aging, joint injury, dysplasia, or other types of arthritis, it results in pain as well as destruction of the larger, weight-bearing joints of the body. Due to a poor understanding of the causes of osteoarthrosis, clinicians often rely on an empirical approach to treatment of this disease. In order to study the causes of osteoarthrosis, researchers have developed an animal model in which degenerative joint disease can be induced by immobilization of the rabbit knee for periods of six weeks or longer. We utilized a 21-day version of this model to investigate the effects of immobilization on the biochemistry and morphology of the cartilage and bone of the rabbit knee.

SIGNIFICANCE Investigators have not uncovered the sequence of events leading up to the development of osteoarthrosis in human beings. Through the use of an animal model, we can employ biochemical and histological techniques to trace the development of pathogenic changes in the knee joint of the rabbit and to gain clues to the development of such changes in humans. Once the cause of this joint degeneration is established, we can investigate the effects of different treatments on the induced osteoarthrosis in the animal model.

BACKGROUND It has been established that mechanical stresses have a significant role in joint biology, but the nature of these stress effects has been disputed. According to one school of thought, immobilization of a joint results in the cessation of important fluid pumping action at the joint surface. It is hypothesized that this pumping of fluid may be a crucial method of supplying chondrocytes with nutrients. Another perspective identifies the cyclic stress history of a joint as the critical factor in joint morphology. Using finite element modelling to predict the patterns of endochondral ossification during development, we hypothesize that cyclic shear stresses promote ossification while cyclic hydrostatic stresses retard ossification and preserve cartilage. We can attribute the thickness and distribution of articular cartilage on a typical mature joint to the large intermittent hydrostatic stresses and the lack of shear stress at the end of a bone. Thus, if we apply this theory to the case of an immobilized rabbit knee, the magnitude of the cyclic hydrostatic stress is reduced, and the articular cartilage degenerates and ossifies as a result.

APPROACH The right hind limbs of 17 adult (4.0 kg, breeder) New Zealand White rabbits were immobilized using splints made of PVC-plastic tubing. We placed the tubing from the proximal thigh to the distal part of the foot and secured it proximally/distally using nylon ties and filament tape. 5-mm holes drilled along the length of the splint insured proper ventilation and cooling of the limb. The splint was designed to insure mobility of the foot and to prevent pressure buildup around the foot.

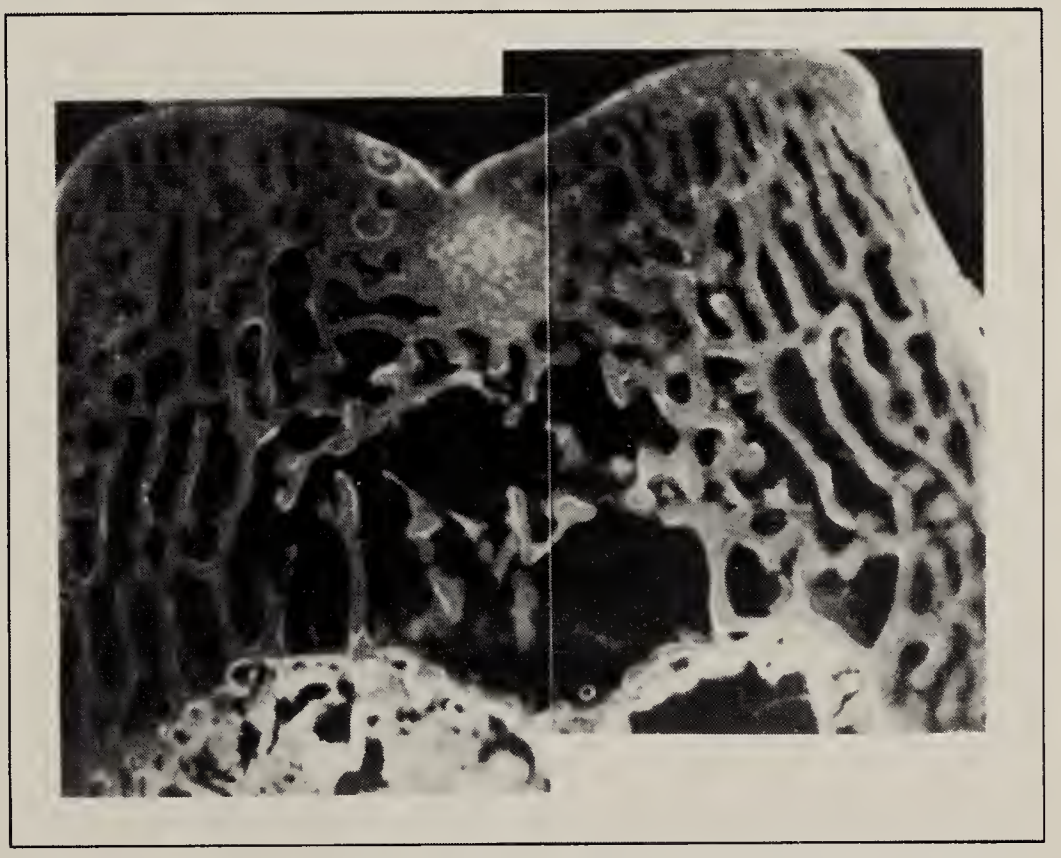

Figure 1. Photograph showing fluorescence of rabbit femur coronal section.

1. Stanford University

Thus the animal could bear weight on the immobilized limb without damaging its foot. Four additional rabbits were used as age-matched controls for comparison of the left and right joints.

Prior to the immobilization studies, the rabbits had 4 weeks to acclimate to their new surroundings. The period of immobilization lasted 21 days. We administered fluorescent labels (adjusted to pH 7.4 prior to injection) in order to document bone turnover during the immobilization period. The first set of 18 rabbits were injected intramuscularly one day prior to immobilization and again one day prior to sacrifice. In addition, we injected this experimental group with radioactive thymidine and sulfate 24 hours prior to sacrifice in order to quantitatively analyze proteoglycan and DNA synthesis. Ten days prior to sacrifice of the second set of three rabbits, an intramuscular injection of Calcein Green (5 mg/kg) was given to each rabbit. Xylenol Orange (60 mg/kg) was injected in a similar fashion three days prior to sacrifice of this second group.

The rabbits were sacrificed by an overdose of phenobarbital, and the hind limbs were harvested so that we could analyze changes in the bone and cartilage of the knee joint using biochemical and histological techniques. We measured dry and wet weights, glycosaminoglycan content, hydroxyproline content, and thymidine and sulfate uptake of cartilage dissected from the first experimental group. Proteoglycans were extracted under dissociative conditions and fractionated on Sepharose CL-2B in the presence of protease inhibitors. Finally, we investigated the morphology as well as bone growth and turnover of all the rabbit joints using fluorescent histomorphometric techniques of undecalcified sections and Safranin-O staining of decalcified sections.

STATUS For the first set of 18 rabbits, gross examination of the articular cartilage surfaces showed a distinct area of vascular eruption on the surface of the lateral tibial plateau and the lateral femoral condyle. We saw no differences in the glycosaminoglycan and collagen content of the surface of the lateral and medial tibial plateaus and the patellar groove, the medial femoral condyle, and the lateral femoral condyle of the immobilized and normal limbs. There was also no difference in the sulfate uptake by the control and experimental tissue. However, the immobilized cartilage had seven times the thymidine uptake per milligram dry weight as the normal cartilage. Also, the bone density of the immobilized femur was markedly decreased. Fluorescent staining of the bone revealed increased bone turnover in the diaphyseal and subchrondral bone of the immobilized tibia and femur.

Although uncharacteristic of osteoarthrosis, the decrease in bone density of the immobilized joint reflects the decrease in joint forces resulting from immobilization. Lower joint forces are related to a decrease in the magnitude of intermittent hydrostatic pressure in the cartilage. As mentioned previously, we feel that cyclic hydrostatic stresses retard ossification and preserve cartilage; thus we would expect to see an increase in ossification and a decrease in cartilage preservation in response to the effects of lower joint forces. It is improbable that the chondrocyte nutrient supply was affected by the immobilization, because DNA synthesis was stimulated. The vascular eruption of the joint surface is indicative of the advance of the ossification front toward the joint surface. All of these observations corroborate the findings of previous joint immobilization studies. These findings are also consistent with out theory of ossification; when the cyclic hydrostatic pressure at the end of the bone is reduced or eliminated, further ossification of the anlage and cartilage degradation occurs.

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Neuromuscular Systems Program

In the Neuromuscular Systems Program three areas of investigation are targeted for research and development:

(1) The biomechanical and electrophysiological properties of the neuromusculoskeletal system.

(2) The coordination of the neuromusculoskeletal system by peripheral and central neural mechanisms.

(3) The development of diagnostic and restorative techniques pertinent to neural and muscular dysfunction.

Research in the first two areas is conducted so that fundamental principles describing the neuromusculoskeletal system can be developed. These principles constitute the basis for our development of rehabilitation techniques and devices for use by the rehabilitation team in reducing the handicap accompanying the person's neuromuscular disability.

To perform this research and development we design and perform experiments to collect electrophysiological, anatomical, kinesiological, and biomechanical data from the neuromusculoskeletal systems of able-bodied and disabled persons. In synergism with our experiments we use engineering analysis techniques to develop computer models so as to formalize the process used in our research and development endeavors. Finally, we use engineering synthesis techniques to transfer these formal notions into hardware (or computer software) packages, either for clinical diagnosis and treatment, or for direct use by the disabled person.

Current emphasis is on:

(1) Developing new methods for rejoining severed nerves and evaluating the subsequent neural regeneration.

(2) Determining optimum functional electrical stimulation (FES) systems for restoring standing and walking to paraplegics.

(3) Developing biomechanical models of the human lower-extremity musculoskeletal system for use in computer studies of both normal and abnormal muscular coordination during posture, walking, and pedaling.

(4) Developing, implementing in hardware, and clinically testing new diagnostic techniques for automatic quantitative analysis of nerve conduction and the electromyogram.

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Intermuscular Coordination of Mammalian Movement

PROBLEM Rehabilitation of persons with severe motor disorders demands an understanding of the neural, muscular, and skeletal mechanisms involved in the control of movement. However, from a control point of view, even the simplest movements are very complex, and multi-jointed movements involving the coordinated action of more than one muscle are at present only poorly understood. The goal of this project is to develop techniques for quantitatively analyzing intra- and interlimb coordination.

SIGNIFICANCE The analytical, computer modeling, and experimental framework being developed in this project will be useful for studying motor tasks involving human lower extremities, such as posture, walking, and pedaling by able-bodied and disabled persons. These computer models will also have use in suggesting optimal strategies for rehabilitation of the motor impaired, for reconstructive orthopaedic surgery, for functional neuromuscular control of paralyzed muscles, and for orthotic and prosthetic design.

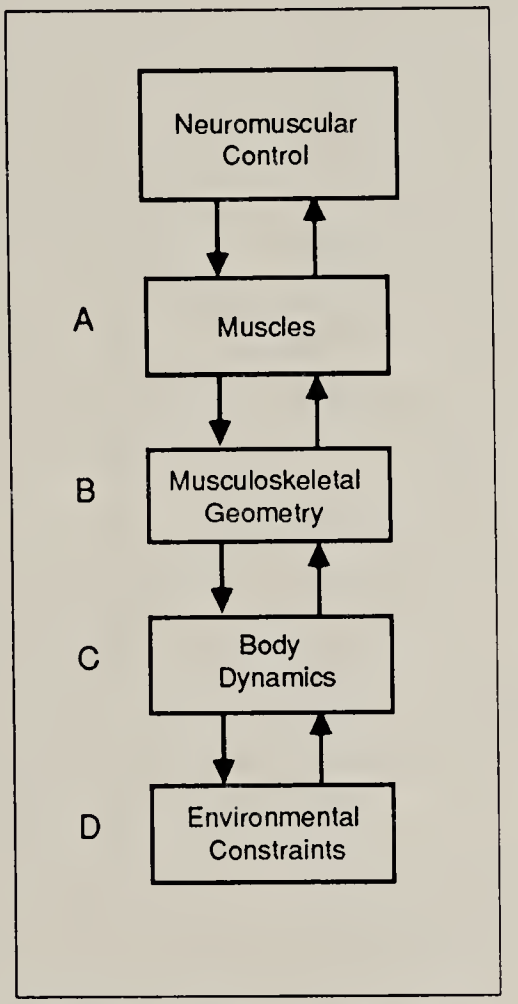

Figure 1. Model of a motor task.

BACKGROUND Motor-control physiologists have studied single-joint movements using electromyographic, kinesiological, single-unit, and *in vivo* force recordings. These studies have resulted in descriptions of the neuromuscular events correlated with the movement under study, but they have led to few predictive theories for motor control.

Biomechanicians, on the other hand, have studied multi-joint movements using dynamical models (similar to ones used to design robots) as a basis for computing joint torques and forces from measurements of body motion. Such studies have been particularly fruitful when applied to the design of artificial joints, but they too have had limited success in enhancing our understanding of neuromuscular coordination and energetics.

HYPOTHESIS Computer modeling of the neuromusculoskeletal system can significantly augment more traditional experimental approaches used to study muscle coordination. Computer modeling applied to control of movement can be used to define the pattern by which muscles ought to be coordinated for the body to achieve a specific motor task. These patterns of control can be defined even when constraints are assumed to be imposed either on the nervous system command-structure (such as may occur in a person who is unskilled in performing a motor task), or on the musculoskeletal system (such as may occur with when a person wears an orthotic brace).

APPROACH Our approach is to study coordination using both computer models and experiments. We are developing a computer model of the neuromusculoskeletal system that will be generally applicable to the study of coordination of human lower limbs. The model can then be applied to the study of specific motor tasks. In addition, we are developing experimental techniques to assess human movements.

We will begin by studying jumping and pedalling, which are relatively simple tasks, yet still pose interesting intra- and interlimb coordination questions. We expect that the computer models and experiments will complement one another, and that the techniques used together will give a more comprehensive understanding

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of muscular coordination. For example, the experimental results will serve to validate the model, and the computer simulation results will provide information that cannot be measured experimentally (*e.g.*, muscle-induced accelerations of body segments).

STATUS Current emphasis has been on the development of a computer model of the human lower extremity. This model consists of three parts, a muscle and tendon model (Figure 1A; see Report 14 for details), a musculoskeletal model of the human lower extremity (Figure 1B; see Report 15 for details), and a dynamical model of the multi-segmental structure of the body (Figure 1C). Each of these models is generic in its representation of human muscles and tendons, musculoskeletal geometry, and body-segmental structure, and can be scaled to represent a specific person by measurement of anatomical and physiological parameters (future work). To use the model to study a specific motor task, it is also necessary to model the interaction between the body and its environment (Figure 1D). Such a model has been constructed for jumping, though it continues to undergo revision, and another is being developed for pedaling.

These four parts of the model are being integrated to allow study of intra- and interlimb coordination of human lower extremity muscles in detail (see Reports 16 and 18). Techniques to monitor body motion, body kinetics, and muscle activity have been synthesized into a Movement Monitoring System for use in experiments on jumping, posture, and walking (see Report 17). In addition, we have applied the computer model to analyze the Chiari hip osteotomy procedure (see Report 19). As a result, we can now recommend specific surgical procedures that ought to improve the current 50% success rate of this surgical operation.

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A Musculotendon-Actuator Model for Use in Studies of Neural Control and Biomechanics of Movement

PROBLEM Detailed computer simulations of the neuromusculoskeletal system require a model of each muscle and tendon (musculotendon actuator) under study.

SIGNIFICANCE Models of musculotendon actuators, when incorporated in musculoskeletal computer simulations, will be useful in studies of neural control, muscular coordination, energetics, and biomechanics of movement. Since few of the significant musculotendon variables (*e.g.*, muscle force, tendon force, muscle fiber lengths, tendon lengths, and rates of muscle contraction) can be measured in humans during movement, musculotendon actuator models are virtually the only means by which to gain knowledge of *in vivo* musculotendon action.

BACKGROUND A large number of muscle models have been proposed. They can be classified into subcellular models and mechanical (input-output level) models. The subcellular models are primarily used to study the molecular and biochemical events associated with muscular contraction and are too computationally complex for studies of coordination. The mechanical models could be used in our study—although specifying model parameters for each muscle would be a major problem—but most of them fail to take into account the effect of tendon, which is an important part of the musculoskeletal system.

Our goal is to construct a new, computationally efficient model of muscle mechanics which takes tendon explicitly into account. The greatest utility comes from a model that is generic in form but can be scaled by specifying a number of parameters to represent any particular musculotendon unit that is of interest.

HYPOTHESIS We hypothesize that a dimensionless, low-order, generic model of musculotendon actuator dynamics can be developed for use in computer studies of movement coordination. We further hypothesize that only a few basic parameters are needed to scale the model to represent a specific actuator or the musculature of a particular individual. Finally, we expect that such a model can be implemented as a set of computer subroutines that can be adapted to a diversity of computer simulations involving muscle and tendon mechanics.

APPROACH Our approach to modeling muscle and tendon is to base the model on musculotendon architecture and fundamental mechanical properties of muscle fibers and tendon. The basis of this formulation is the arrangement of muscle fibers with respect to tendon

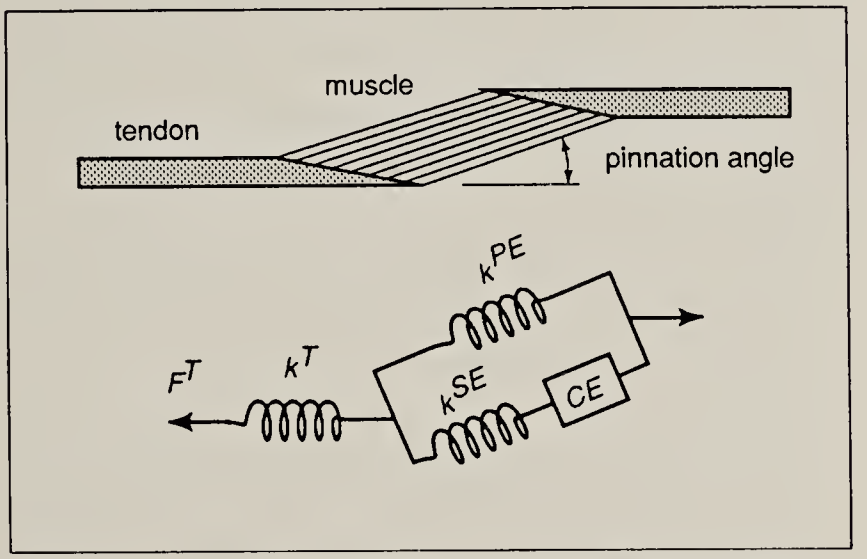

Figure 1. Mechanical model of pinnate musculotendon actuator.

(pinnation angle), the arrangement of sarcomeres within a muscle fiber and fibers within a muscle, the mechanics of sarcomeres when passive and activated, the dynamics associated with excitation-contraction coupling, and the constitutive (stress-strain) properties of tendon. Tendon is modeled as an elastic element whose stiffness increases with force to a threshold value. The model is structured (Figure 1) so that its dynamics are low-order and dimensionless. It can also be scaled to emulate the force-length, force-velocity, elastic, and activation properties of muscle and tendon.

STATUS We have developed a dimensionless, first-order model of musculotendon contraction dynamics. Only three actuator-specific parameters (muscle strength,

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optimal muscle fiber length, and tendon slack length) are needed to scale the generic representation to a specific actuator. When muscle fiber orientation is considered, the model changes only in algebraic complexity, though another actuator-specific parameter is required.

We consider muscle to generate force in proportion to some level of activation. This activation is related to the electrical activity of muscle signal, but is not equal to it. Instead, we model a dynamic response that we refer to as activation dynamics. The dynamics associated with muscle activation are modeled as first order differential equation decoupled from the contraction dynamics. Thus, the complete dynamics used to describe musculotendon mechanics consists of two first-order differential equations.

The musculotendon actuator model has been implemented as a set of FORTRAN subroutines and can be easily be adapted to computer simulations. To date we have shown that tendon can be a dominant factor in musculotendon mechanics and that the degree to which musculotendon properties are affected is muscle-specific, at least for human lower extremity muscles.

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SUPPORT

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Development of a Musculoskeletal Model of the Human Lower Extremity

PROBLEM Computer simulation studies of the human neuromusculoskeletal system are needed to understand the function of different muscles during movement. Thus, a musculoskeletal model of the human lower extremity must be developed to study intermuscular coordination of even such apparently simple movements as standing and walking.

SIGNIFICANCE Besides our use of models to understand how muscles are coordinated during standing and walking in able-bodied persons, we can also use musculoskeletal models to determine the optimal coordination to compensate for lost muscle function in disabled persons. Such understanding will greatly contribute to our efforts to design functional electrical stimulation (FES) systems for persons with paralyzed lower extremities. For example, simulation of the musculoskeletal system can help determine which muscles should be stimulated, and what pattern of activation should be used, during standing and walking using FES.

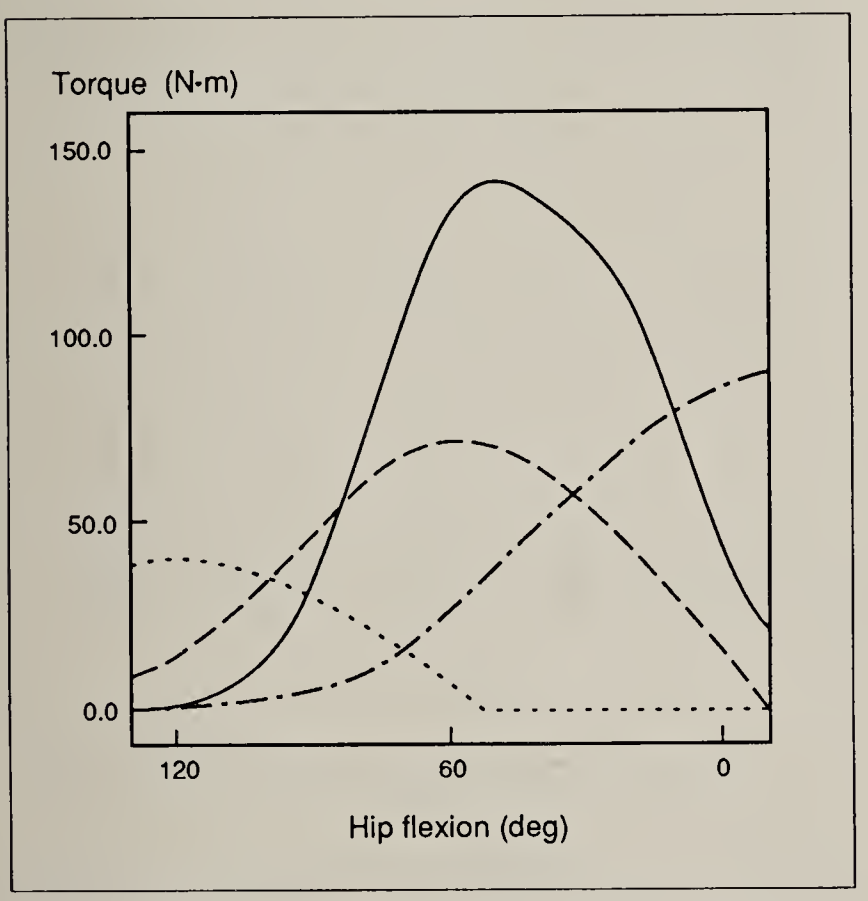

Figure 1. Hip extensor torque generated by hamstrings (solid line), adductor magnus (dashed line), adductors longus and brevis (dotted line), and gluteus maximus, medius, and minimus (dashed dotted line).

BACKGROUND To understand intermuscular coordination, the ability of each muscle to produce torque about a joint must be quantified. Human muscles cannot usually be instrumented *in vivo* to measure muscle forces and torques during movement. Typically, muscle function is inferred from patterns of myoelectric activity, limb displacement, and ground reaction forces which are recorded during experiments and analyzed with inverse dynamics methods. As an alternative, muscle function can be assessed using mathematical models of the human musculoskeletal system. With such models, basic mechanisms of intermuscular coordination can be investigated, such as the torque-producing capability of individual muscles, musculotendon energetics, and neural constraints on muscle activation. Simulations can be used to understand why muscles are coordinated as observed in able-bodied persons, or to determine how best to activate muscles in paralyzed persons using FES.

HYPOTHESIS A comprehensive musculoskeletal model of the human lower extremity can be developed which will adequately represent muscle mechanics and musculoskeletal dynamics so that physiological muscle forces and torques are predicted, individual muscle function is determined, and intermuscular coordination is assessed.

APPROACH To understand muscle function, both the force-producing capability of individual muscles and the geometry of the musculoskeletal system must be considered. Muscle force can be described by a single, dimensionless musculotendon model (see Report 14); however, the musculotendon model must be scaled to individual muscles by three parameters: the peak isometric force, the optimal muscle fiber length, and the tendon slack length. Specification of the musculoskeletal geometry is important because it determines (1) moment arm, and

therefore, the magnitude of muscle torque generated by a given muscle force, and (2) muscle force, since muscle force varies with musculotendon length, which is a function of musculoskeletal geometry.

STATUS We have developed a musculoskeletal model of the human lower extremity to study muscle function in the sagittal plane. With our model, we have specified the musculotendon parameters and musculoskeletal geometry for eighteen muscles acting at the hip, knee, and ankle joints. Because of differences in tendon slack length, optimal muscle fiber length, and moment arm among muscles, we found that the joint angle where each actuator develops peak isometric torque is different, even among muscles that generate torque in the same direction at a joint (see Figure 1). The joint angle where a muscle generates peak isometric torque does not necessarily coincide with the joint angle of: (1) peak muscle force, (2) peak moment arm, or (3) peak torque developed by maximum voluntary contractions. By characterizing the torque-producing capability of each muscle, our model provides a basis for understanding intermuscular coordination in both able-bodied and disabled persons.

In the future, we plan to expand the model to study muscle function in the frontal and transverse planes. Since the muscle parameters are scalars and the musculoskeletal geometry is already specified in three dimensions, only the joint models need to be modified. We plan to refine the joint models by representing the joint kinematics in greater detail, even in the sagittal plane, thus accounting for the known characteristics of the joint kinesiology. Also, the metatarsophalangeal joint will be incorporated in the model to study intermuscular coordination during propulsion.

ACKNOWLEDGMENTS

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SUPPORT

National Institutes of Health (1985-present)
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Neuromuscular Control and Biomechanics of Jumping

PROBLEM Motor tasks for which relatively simple computer models can be developed and that still pose challenging intra- and interlimb coordination questions must be studied using computer modeling and experimental techniques. Specifically, it is necessary to show that these techniques can be used to comprehend the energetics associated with these motor tasks. We need to determine how energy produced by a collection of muscles is stored in their musculotendon actuators and transferred from either one actuator to another or to the mass segments of the body.

SIGNIFICANCE By showing that computer modeling and experimental techniques together can be used to understand coordination better than each technique in isolation, we will have demonstrated the utility of computer models in studies of movement. A similar approach can then be used to study even more complex movements, including those of disabled persons, fostering the notion of design of rehabilitation strategies based on computer techniques (*i.e.*, rehabilitation based in part on computer-aided design methods).

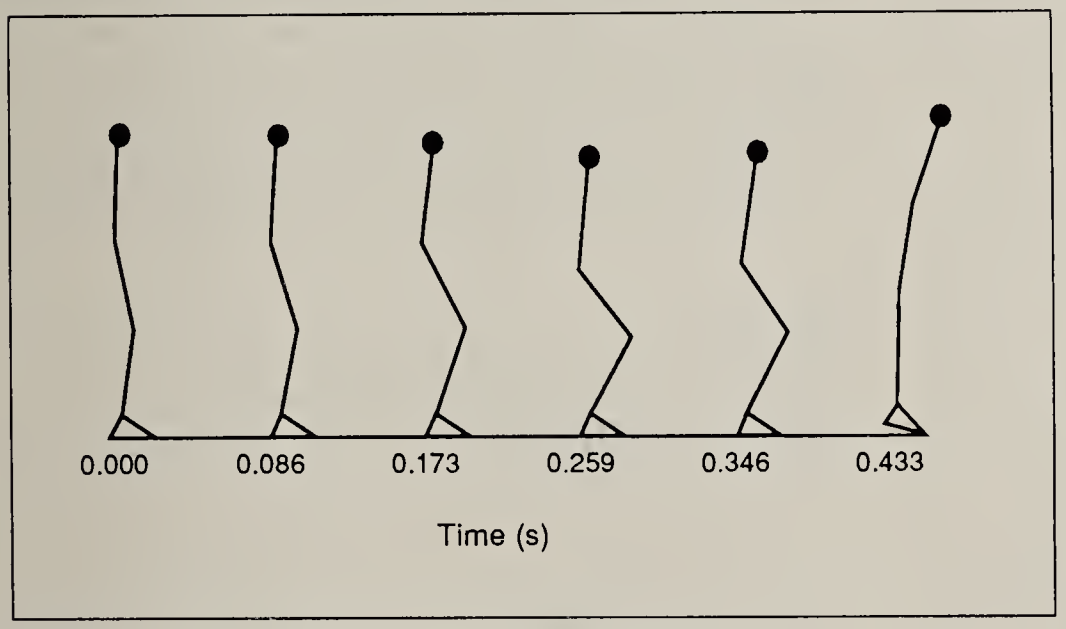

Figure 1. Body positions during a simulated jump.

BACKGROUND Our past work has focused on the understanding of the importance of the various components involved in neuromuscular control (see Report 13), using jumping as an example of a reasonably complex motor task. It became apparent from this work that one of the critical voids in the development of a musculoskeletal computer model was a generic model of both the musculotendon actuator and the geometrical properties of the human lower extremity (see Reports 14 and 15). We also became aware of the difficulty in finding reliable computer code that could be used to find, once the neuromusculoskeletal dynamics was specified, how the muscles ought to be optimally coordinated to maximize some given performance criterion (*e.g.*, in jumping, the criterion is to maximize the height of the jump). Finally, our experimental studies of jumping indicated the necessity of conducting ongoing experiments in symbiosis with computer modeling studies.

HYPOTHESIS Data from computer models of the neuromusculoskeletal system can enrich one's comprehension of the energetics and coordination of jumping specifically, and movement in general.

APPROACH Our approach is to study the coordination and energetics of jumping using both computer simulations and experiments. In some simulations, we are using a simple representation of the articulations of the body in order to define the elements of both the musculotendon actuator and the musculoskeletal system. In so doing, we can also delineate the rudimentary properties of jumping energetics. In parallel with this study, we are developing a complex neuromuscular control model of jumping that includes eighteen human lower extremity muscles acting on four articulated body segments. The investigator can either specify *a priori* a set of muscle activation (coordination) patterns or run an optimization algorithm to compute the best pattern.

Concurrent with these simulation studies, we are developing a movement monitoring system for use in experiments on human jumping, posture, and gait (see Re-

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port 17). With the system, we can quantify body motion, muscle activity, and ground reaction forces during motor tasks.

STATUS With the simpler computer model of the body, we studied jumps where propulsion was supplied by only one muscle, the quadriceps muscle (located on the front of the thigh). From these results, we were able to define the structure of the musculotendon actuator that needs to be modeled for computer studies of jumping and coordination (see Report 14). We found that the musculotendon actuator, in this case the quadriceps, can perform operationally in different ways, *e.g.*, in jumping from a squat the actuator principally generates the work output needed to propel the body upwards, whereas in jumping subsequent to a fall, the actuator principally acts like a spring, storing the energy during the fall and then releasing the stored energy to the body during propulsion. We are currently studying jumps with the more sophisticated model of the body (see Figure 1).

Preliminary results indicate that musculotendon energetics are determined by the unique properties of each musculotendon actuator and their interaction with the skeletal dynamics. For example, the percentage of the elastic energy stored in tendon in the downward phase of the jump was greater for the calf muscles (specifically, gastrocnemius muscle) than for the quadriceps muscles (specifically, vasti muscle) because gastrocnemius has a relatively more compliant tendon than vasti. To find the best muscle coordination for a person of a given physique, we are developing optimization algorithms. These algorithms have been conceptualized, computer coded, tested, and checked using a musculoskeletal model of intermediate complexity.

Using this optimization model we are now collecting data to learn how muscles and the body segments interact to coordinate the motor task. In addition, we are now implementing the more complex model of the human body into the optimal control algorithm and expanding the capabilities of the optimization algorithm to study how sensitive muscle coordination is to body physique and to the posture that the body has before the jump.

ACKNOWLEDGMENTS

We thank Peter Loan and Art Wong for their assistance in data analysis and computer programming.

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SUPPORT

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Human Movement Monitoring System to Study Posture, Walking, and Jumping

PROBLEM We have developed computer models for simple motor tasks such as posture, gait, and jumping (see Reports 13, 16, 21 and 23). To verify these models and to assess musculoskeletal disabilities associated with these tasks, it is necessary to simultaneously record the body positions, muscle activities, and ground reaction forces from each patient during movement.

SIGNIFICANCE Developing an experimental system that simultaneously monitors three-dimensional body positions, muscle activities, and ground reaction forces during movement will make possible more complete analyses of complex motor tasks. This will allow us to accurately record the exact sequence of kinesiological events during motor tasks. Such records will be important for defining rehabilitation strategies to restore mobility to disabled persons with severe musculoskeletal disorders. These data will also be useful in assessing computer models that have been developed for posture, gait, and jumping.

BACKGROUND Our monitoring system consists of three primary components, indicated in Figure 1: (1) the Selspot II system for measuring limb positions, (2) electromyographical (EMG) instruments for measuring muscle activity, and (3) force plates for measuring ground reaction forces during movement. In the past, however, it has been impossible to collect Selspot, EMG, and force plate data simultaneously because of the large size of the software programs that control the Selspot system. EMG and force plate data during an experiment had to be recorded on an analog tape recorder. Synchronizing these data with the Selspot data was difficult and resulted in unacceptable experimental error. Therefore, we needed to modify the Selspot software, the existing analog-sampling software, and the memory configuration of the computer to record the data simultaneously with a single computer.

HYPOTHESIS A single computer can be configured to simultaneously record three-dimensional body positions, muscle activities, and ground reaction forces. The Selspot software can be altered so that all data are collected by the same sampling routine, thus ensuring that the data can be synchronized with a high degree of accuracy.

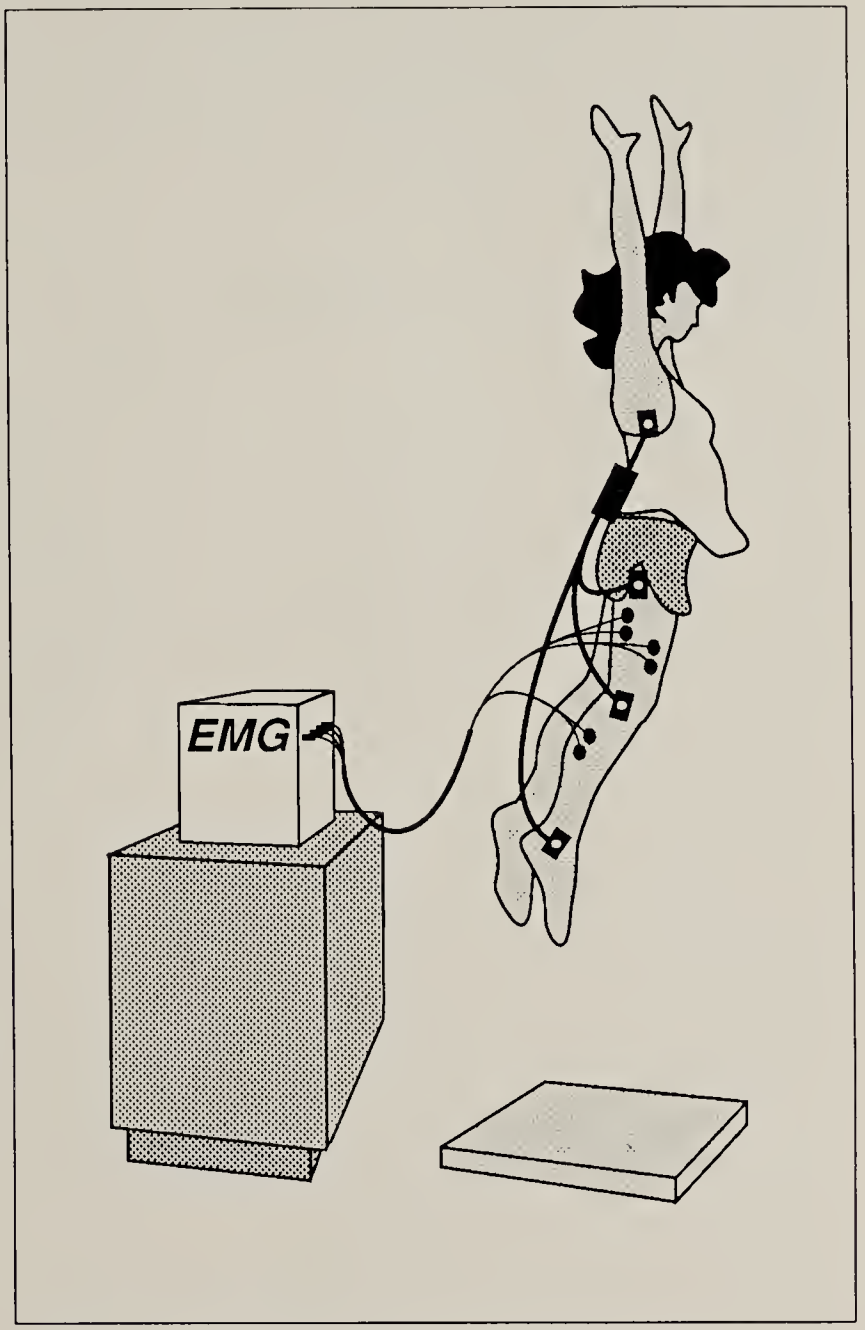

Figure 1. Monitoring system with Selspot LED assemblies, EMG electrodes and force plate.

APPROACH To sample body position, muscle activity, and ground reaction force simultaneously, we modified the memory configuration of the PDP-11/34 to allow for larger computer programs. In addition, the computer pro-

grams themselves were reduced in size. A digital data generator was built to check the accuracy of the resulting routines.

STATUS With a single computer, we can simultaneously record data from sixteen peripheral channels and the Selspot system for a maximum period of ten seconds. Programs are being revised so that the Selspot software will initiate the sampling of analog data, thus ensuring that the data are synchronized with a high degree of accuracy. Once the data are collected and formatted, data are transferred from the PDP-11/34 to the VAX 11/780 for further analysis. To facilitate data analysis, we have developed software to display and analyze the data on an IRIS 2400 graphics workstation. Video equipment has been integrated into the laboratory and will provide important qualitative information.

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Dynamic Interpretation of Muscle-Functional Roles During Cycling: A New Approach to Lombard's Paradox

PROBLEM The classical method of defining a muscle's functional role is inadequate to explain the body's use of the rectus femoris (RF) and hamstrings (HAMS) muscles during cycling (see Figure 1). Cycling requires similar motion at the hip and knee: both extend during the power stroke and both flex during the recovery stroke. Classically, however, both RF and HAMS are considered to produce opposite motions at these two joints: RF is thought to flex the knee and extend the hip, HAMS to extend the hip and flex the knee. The seemingly paradoxical use of RF and HAMS during cycling has been termed Lombard's Paradox.

To date there is no method of specifying muscle functional roles that can explain Lombard's Paradox and adequately interpret muscle activity during cycling.

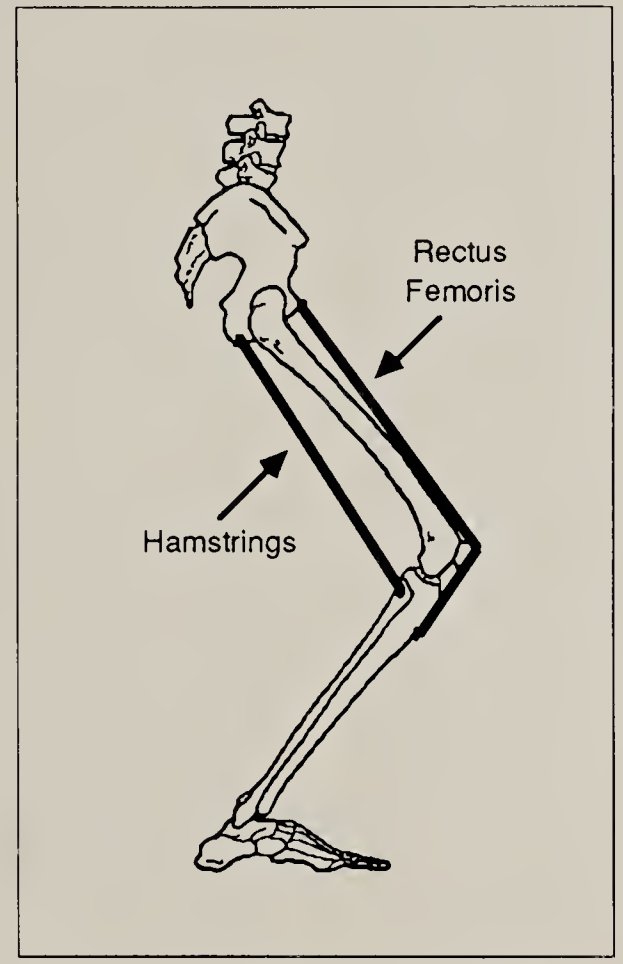

Figure 1. Anatomical locations of the rectus femoris and hamstrings muscles. Both muscles cross the hip and knee joints, but on opposite sides of the thigh.

SIGNIFICANCE A new method of defining muscle functional roles that could explain observed muscle activity during cycling would provide valuable insight into muscular function and coordination during other motor control tasks as well. These tasks include standing from a seated position, restoration of posture and walking. In addition, such a method could lead to the development of prescribed patterns of electrical stimulation for exercising and restoring strength to paralyzed muscles through tasks such as pedaling a stationary bicycle.

BACKGROUND The classical method of specifying muscle functional roles is based on the premise that a muscle will try to move a joint it spans in the direction of its applied moment. For example, a muscle like HAMS which crosses the back of the knee is thought to always cause the knee to flex. Since the classical method is not based on dynamics, it does not take into account the variety of limb positions possible for a task and hence ignores the possibility of a muscle changing its functional role with changing limb position. This method also neglects a muscle's dynamic influence at joints not spanned by the muscle.

Based on the classical method, biomechanists consider observed RF and HAMS activity during cycling to be paradoxical (i.e. seemingly contradictory to the motion desired) for two reasons. The first reason (Lombard's Paradox) is that neither RF nor HAMS is considered capable of producing the simultaneous hip-knee flex or extend motions required for cycling. Each muscle appears to exert a moment in the desired direction at only one joint, while exerting a seemingly unwanted moment at the other. The second reason is that RF and HAMS both demonstrate electromyographic (EMG) activity during the early part of the crank cycle. EMG activity reflects the level of a muscle's electrical activity and is used by researchers as an indication of how much force a muscle produces. Since RF and HAMS cross the hip and knee on opposite sides of the body, they are regarded as having opposite functional roles at these joints. It is therefore paradoxical from an energy-efficiency point of view that these two seemingly opposing muscles would ever be activated simultaneously.

HYPOTHESIS We would like to develop a new methodology for specifying muscle functional roles that explicitly takes the dynamics of the affected body segments into account. This methodology will be based on the dynamic equations of motion that describe how the body segments move under the influence of all applied forces. We believe this methodology will explain observed muscle activation patterns better than the classical method.

APPROACH Our lab has developed a new method of defining a muscle's functional role which stems from the system equations of motion. This method uses the directions in which a muscle tries to angularly accelerate all body segments (and hence all joints) as an indicator of a muscle's action on the body [1]. For example, a muscle which accelerates a joint toward flexion is considered to act as a flexor of that joint, whether or not the muscle actually spans the joint. The action of any single muscle can be specified by computation of that muscle's contribution to the total segmental accelerations while ignoring acceleration contributions made by all other muscles.

In order to apply the new method to a specific problem, a model must first be developed from which the system equations of motion can be derived. Once the model is developed, all system configurations must be determined for which muscle functional roles are desired. Next, the distance from each muscle to each of its spanned joints (i.e. the moment arms of the muscle) must be computed over the specified range of system configurations. Finally, for any system configuration, the direction and magnitude that each muscle accelerates all body segments can be computed per unit force in the muscle.

STATUS We have derived the system equations of motion for a three degree-of-freedom planar model of a cyclist on a stationary bicycle. System parameters can also be chosen to simulate the dynamic response of a cyclist on an actual bicycle. We included both legs in our model since pedal reaction force data indicates that the power leg actually propels the recovery leg through the recovery stroke. In this way, we can investigate the influence of one leg on the other, which, though negligible for a rider on an actual bicycle, is sizable for a rider on a stationary bicycle.

We are currently specifying the functional roles of six lower extremity muscles for the entire crank cycle and displaying the results on our graphics workstation as an animated cyclist. The new and old methods of specifying muscle functional roles seem to be in agreement for single-joint muscles at the joints they span. However, for two-joint muscles, we have obtained very nonintuitive functional role specifications with the new method which are not in agreement with the old method.

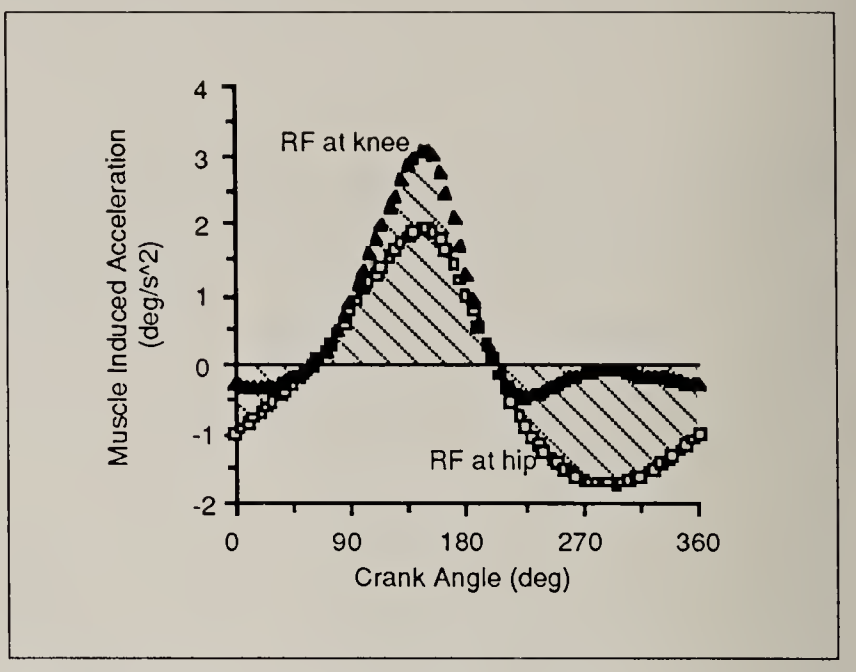

Figure 2. Joint accelerations induced by RF at the hip and knee. Positive acceleration is toward extension, while negative is toward flexion. Shading highlights the similar acceleration directions at both joints.

We have found that the direction of a two-joint muscle's applied moment is not necessarily the direction in which the muscle acts to accelerate the joint. Our specification of muscle functional roles indicates that during cycling of an actual bicycle, RF and HAMS always act to accelerate the hip and the knee in similar directions. At the beginning and end of the crank cycle RF acts to accelerate the hip and knee toward flexion, while in the middle of the crank cycle it acts to accelerate both joints toward extension (see Figure 2). In contrast, HAMS always acts to accelerate the hip and knee toward extension. We are currently investigating the implications of these results on Lombard's Paradox in light of observed EMG activity and desired total joint moments and accelerations.

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SUPPORT

National Institutes of Health (1982-present)
RR&D Core Resources

Scott L. Delp MS
Felix E. Zajac PhD
Eugene E. Bleck MD[1]
Gerard Bollini MD[2]

Musculoskeletal and Biomechanical Analysis of the Chiari Pelvic Osteotomy

PROBLEM Generally, people with a hip joint deformity called dysplasia are in great pain and must undergo surgery to correct their deformity. One surgical technique, the Chiari pelvic osteotomy, has become widely used to treat hip dysplasia. Although the Chiari osteotomy is usually effective in reducing pain, many patients are left with a long-term limp. The limp occurs when the hip abductor muscles cannot counteract the torque from gravity and thus the pelvis sags during single leg stance.

SIGNIFICANCE Using surgical technique that conserves hip abductor torque may reduce the number of instances of the post-surgery limp. Our objective, therefore, is to understand how each surgical parameter (see Figure 1) affects hip abductor torque. With this information we can determine if a specific surgical technique would greatly reduce abductor torque and find a surgical technique that conserves abductor torque.

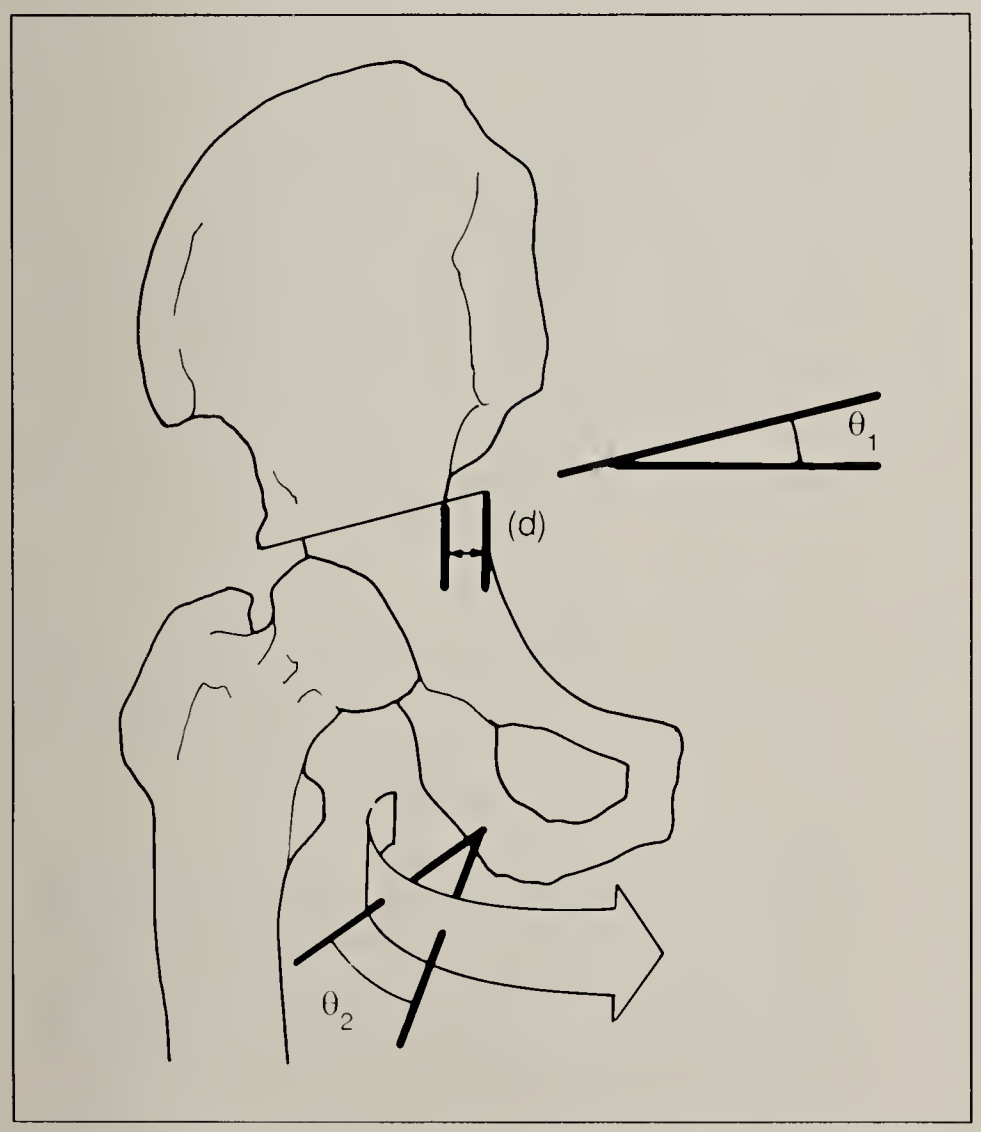

Figure 1. Surgical parameters. θ_1 is the angulation of the osteotomy, d is the distance of medial displacement, and θ_2 represents the relative rotation of the two bone fragments.

BACKGROUND Subluxation of the hip with secondary acetabular dysplasia is particularly difficult to manage when it becomes irreducible. To solve this problem Chiari devised a medial displacement osteotomy of the pelvis. In Chiari's procedure, a cut is made through the ilium dividing it into two pieces. The distal fragment is then displaced medially to create a bony ceiling above the femoral head. Increased femoral head coverage improves hip joint stability.

Since Chiari's procedure displaces the hip joint medially, it reduces the abductor torque required to counteract the torque from gravity. It is puzzling, however, that a procedure which actually reduces abductor torque requirements, often leads to a limp (Trendelenburg gait) characterized by an abductor torque deficit.

HYPOTHESIS We hypothesize that surgical modification of the musculoskeletal geometry may substantially reduce hip abductor torque and thus cause the limp.

APPROACH To understand how each surgical parameter affects hip abductor torque, we developed a computer model to simulate the changes that occur during the surgical procedure. The model is composed of two parts: (1) a surgical model which computes the post-surgery hip joint geometry, given values for the surgical parameters, and (2) a musculoskeletal model which calculates the changes in hip abductor torque resulting from the changes in musculoskeletal geometry.

To initiate a surgery simulation, we entered values for each surgical parameter. The surgical model then computed the post-surgery hip joint

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geometry. These intermediate results were entered into the musculoskeletal model, where post-surgery hip abductor torque was computed for joint angles ranging from –15°to 50° of abduction. Both pre-surgery and post-surgery torques were then plotted against joint angle.

STATUS Using both surgical and musculoskeletal models we have simulated hundreds of surgeries and found that some sets of surgery parameter values conserve abductor torque while others largely reduce it. For example, with 15-mm of medial displacement, –5° of angulation, and 10° of internal rotation, the post-surgery abductor torque was reduced by only 10 per cent at anatomical position (see Figure 2). In contrast, with 30-mm of medial displacement, 30° of angulation and 10° of internal rotation, post-surgery abductor torque was reduced by 65 percent at anatomical position (see Figure 3). The decrease in abductor torque occurred primarily because of shortened muscle path. We therefore recommend that the angulation of the osteotomy be kept near horizontal to preserve muscle length and hip abductor torque.

These results have been presented to several groups of orthopaedic surgeons in addition to the conferences noted in the publication section. We are now preparing the final manuscript for publication in an orthopaedic journal.

PUBLICATIONS

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SUPPORT

National Science Foundation Fellowship (SLD)
RR&D Core Resources

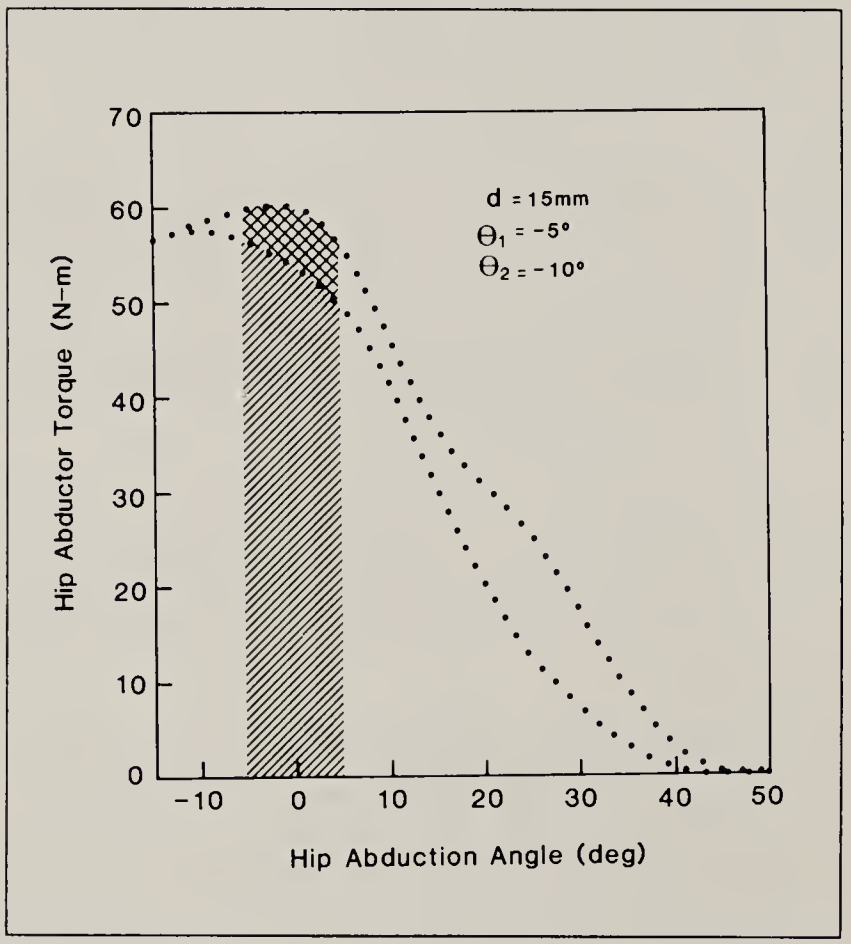

Figure 2. Results of a surgery simulation showing conservation of abductor torque. Pre-surgery torque (upper curve). Post-surgery torque (lower curve). The shaded area represents the range of hip abduction used in walking and the cross-hatched area highlights the difference between pre-surgery and post-surgery curves.

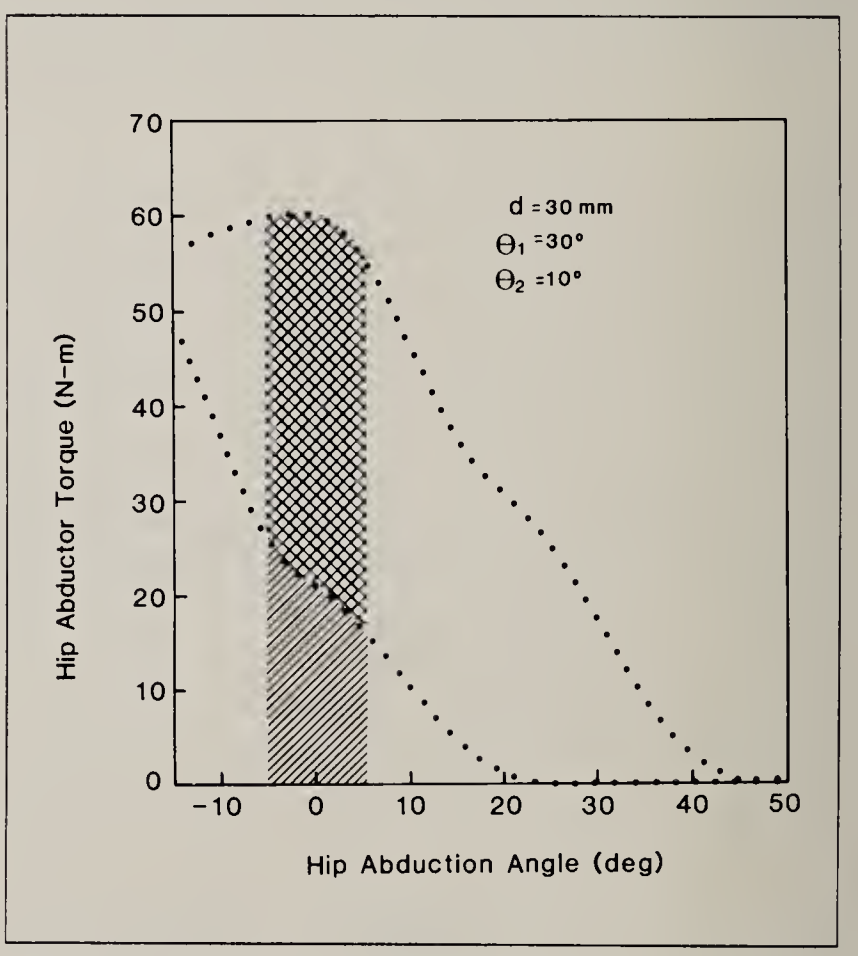

Figure 3. Results of a surgery simulation showing large reduction of abductor torque. Pre-surgery torque (upper curve). Post-surgery torque (lower curve). The shaded area represents the range of hip abduction used in walking and the cross-hatched area highlights the difference between pre-surgery and post-surgery curves.

Felix E. Zajac, PhD
Inder Perkash, MD

Computer Models for Designing Functional-Electrical-Stimulation Systems for Paraplegic Standing and Walking

PROBLEM Persons with spinal cord injury resulting in paraplegia need to regain functional use of their legs. Functional electrical stimulation (FES) of nerves going to paralyzed leg muscles has shown that paraplegics can stand and step. Unfortunately, there remain technical problems that must be resolved before natural-like standing and walking become possible, and before such applications of FES become a clinical reality. One of these problems is lack of knowledge of the trade-offs among alternative designs of FES systems.

SIGNIFICANCE Functional electrical stimulation to restore mobility has potential for wide use among those paraplegics whose spinal cord after injury retains many intact nerves. This project's goal is to use computer techniques to design FES systems and to study the trade-offs among alternative designs. Eventually, this work will lead to computer-aided design techniques so that systems can be constructed enabling each paraplegic-user to achieve maximum performance. Such computer-modeling studies and design methods should lead to improved user acceptance of FES systems, reduce the risks-to-benefits ratio for patients who are candidates for implanted FES systems, and reduce the amount of experimentation needed to develop clinical FES systems for restoring mobility to paraplegics.

BACKGROUND Functional electrical stimulation of paralyzed muscles is potentially a useful method for restoring standing and walking in paraplegics. Problems exist, however, that must be solved before FES becomes clinically acceptable as a mechanism for restoring mobility to paraplegics. These problems include unreliable stimulating electrodes, insufficient muscle strength and fatigue resistance of the paralyzed muscles, and unavailability of a totally implantable stimulation system. Another problem is the lack of suitable engineering models to study the trade-offs among alternative FES schemes proposed for controlling paraplegic standing and walking.

HYPOTHESIS We hypothesize that the use of large-scale computer models based on engineering principles is essential to the systematic development of FES systems, just as such models are necessary in controlling aircraft, satellites, robots, and in planning economic policy.

APPROACH Our approach is to pursue three objectives simultaneously. One objective is to formulate a control problem of standing and walking, implement the control problem on a computer, and study the trade-offs among alternative control schemes. The computer-simulated control problem consists principally of a model of the musculoskeletal system being controlled, a model of the feedback sensors employed, and a feedback controller whose properties are to be chosen by optimizing some performance criterion. Another objective is to understand the functional significance of individual muscles to maintenance of upright posture, with emphasis on identification of functional muscular synergies. To ac-

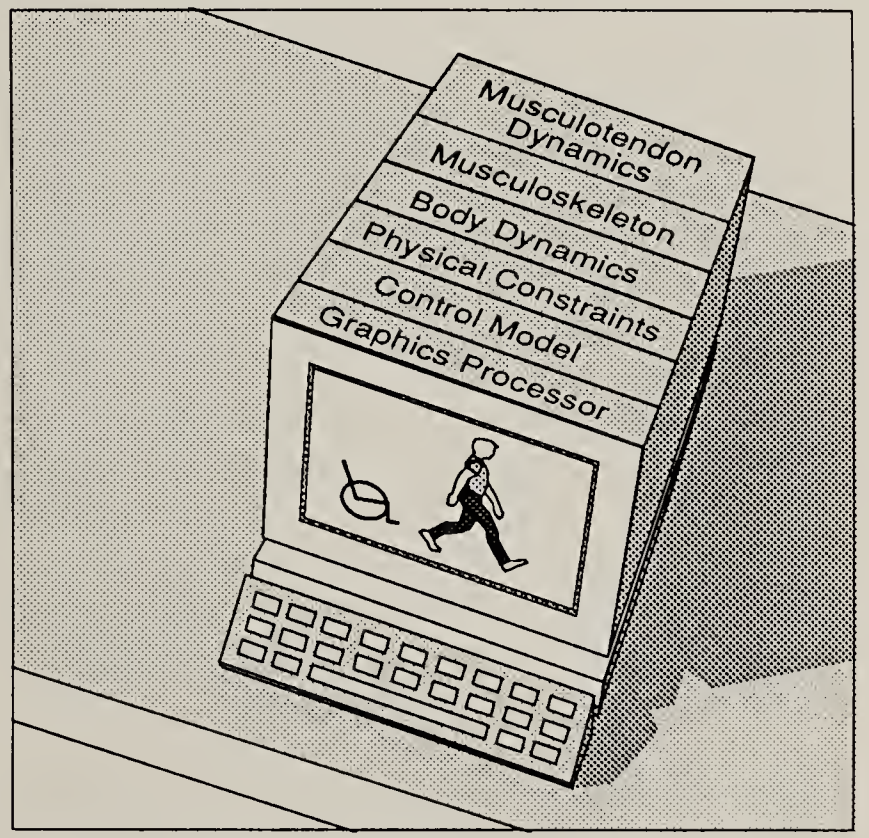

Figure 1. Program overview.

complish this objective we are using a computer model of the musculoskeletal system and focusing on the mechanics and geometry associated with posture and the imposition of various physical constraints, such as keeping one's knees fully extended or feet flat on the ground. A final objective is to place in operation a state-of-the-art graphics workstation to display in real-time an animation-like simulation of the human body under FES control. This final objective is predicated on the assumption that computer graphics and simulation is an effective communication medium for the rehabilitation team, especially one with members of disparate training, as quite commonly occurs.

STATUS We have developed a computer model of the control of posture in paraplegics, assuming a FES system is used to activate and control the paralyzed musculature (see Report 22). Studies based on this model suggest how to activate muscles to control paraplegic posture with energetic efficiency. These schemes indicate how muscles should be coordinated to restore upright posture from, say, a seated position, and what sequence of activation of muscles is needed to maintain posture when paraplegics move their arms, as when they reach for objects.

Currently we are using the model to study how physical parameters of the body (*e.g.*, muscle strength and fatigue resistance) and parameters of the FES system (*e.g.*, number of stimulation channels) affect the ability of a paraplegic to stand. We have developed another model of posture that is being used to define how far from the upright posture the body can be perturbed without the paraplegic falling over (see Report 21). Results from this model also suggest that there may be specific synergies of activation of muscles that are conceptually simple, yet quite effective in restoring posture. The identification of these synergies is needed because less computationally demanding controllers for FES systems are required if practical implementation is to be imminent.

Though much less far along in development, we are also formulating models and implementing them on the computer to study designs of FES systems that have potential in restoring natural gait to paraplegics (see Report 23). The basic issue to be studied is what are the requirements that muscles must meet (*e.g.*, strength), and how can a limited set of muscles (since only a limited set is available to FES systems) be coordinated to restore not only stepping, but walking that looks similar to an able-bodied person.

To display animation-like simulations of our computer-generated data of standing and walking, we now have in operation a high-performance graphics workstation (see Report 25). We currently are developing programs for the workstation so that it will become not only an informative display device, but an investigative tool as well.

Finally, we have completed the development of a simple mechanical representation of the knee that simulates its essential mechanical properties (see Report 24). Currently, we are computer-implementing and integrating this representation into our overall musculoskeletal computer model of the lower extremity.

SUPPORT
VA RR&D Merit Review (1986-present)
RR&D Core Resources

Michael E. Gordon, MS
Felix E. Zajac, PhD

The Muscular Biomechanics of Human Posture

PROBLEM Persons with paraplegia need to regain functional use of their legs. Since the ability to maintain upright posture is so fundamental to standing and walking, the restoration of upright posture is an important first step towards the restoration of functional use of the legs. The goal of this project is to study the biomechanics and muscular coordination of posture in order to learn how best to design systems for restoring posture to paraplegics.

SIGNIFICANCE Functional electrical stimulation (FES), a method in which paralyzed muscles are directly stimulated under computer control, is potentially a useful method for restoring posture and movement to paraplegics. Knowledge gained in this project will help us to decide which muscles to stimulate and how to coordinate them to control posture effectively using FES.

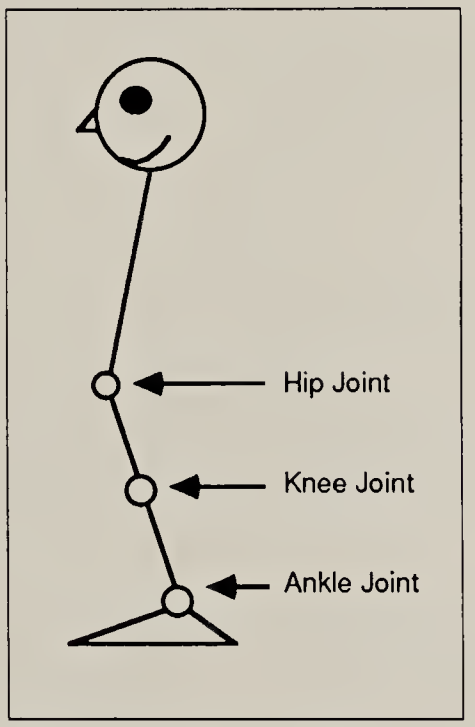

Figure 1. Skeletal model.

BACKGROUND Human upright posture is sustained with the fine coordination of many muscles. However, it would be unnecessarily complicated to design an FES control system that activates many muscles separately. Experimental research suggests that to maintain upright posture, only a few different combinations of the many individual muscles are normally used. These combinations are termed synergistic muscle groups, or *synergies*: groups of muscles that work together to maintain upright posture. The experimental identification of synergies is limited because experiments are unable to discriminate between the activities of nearby muscles and are unable to monitor the function of deep muscles.

HYPOTHESIS It is hypothesized that the groups of muscles normally used to maintain posture are those used to maximally accelerate the body from a disturbed position towards the upright standing position.

APPROACH An engineering model, based on the important properties and parameters of the human body, has been developed (see Figure 1). The body is represented as four rigid segments: foot, shank, thigh, and torso. The musculoskeletal system is modeled in detail, and 14 muscles of the ankle, knee, and hip are included (see Report 15). Muscle and tendon are represented by a generic model which is adapted to each individual muscle and tendon by the parameters of muscle strength, muscle fiber length, and tendon slack length. We considered initial body positions of either leaning forwards or backwards, with the knees fully extended and the feet flat on the ground.

Optimization techniques were used to identify the synergies or muscle combinations that should be stimulated to maximally accelerate the body towards upright standing, and also to identify the body positions for which each synergy is effective. In addition, optimization methods were used to determine quantitatively how the physical constraints, such as keeping the knees fully extended, limit the ability to maintain an upright standing position.

STATUS The computer model has been developed and thoroughly tested. The results predict synergies that are consistent with certain experimental work. Because muscles can only pull and not push, the different synergies are effective in only certain body positions. Whereas some muscle synergies contain muscles on only one aspect of the body (front or back), other synergies contain muscles on both. Figure 2 shows the range of body positions when muscles on only one side of the body are activated: synergy I consists of all muscles on the front, and synergy II consists of all muscles on the back. As can be seen from the figure, the use of either synergy I or synergy II is restricted to a portion of the body posi-

tions. For body positions outside the regions shown, synergies with muscles on both sides of the body are activated.

The results identify the separate contributions of muscles, such as soleus, which had been neglected or grouped with other muscles. Also, the optimization results provide insight into the specific way in which posture is recovered. For example, should the upper body recover first or should the leg? It appears that the physical constraints severely restrict direct acceleration towards the upright position. Insufficient muscle strength is not the primary problem. The major difficulties are keeping the feet flat on the ground and keeping the knees in the fully extended position. This work is being prepared for publication.

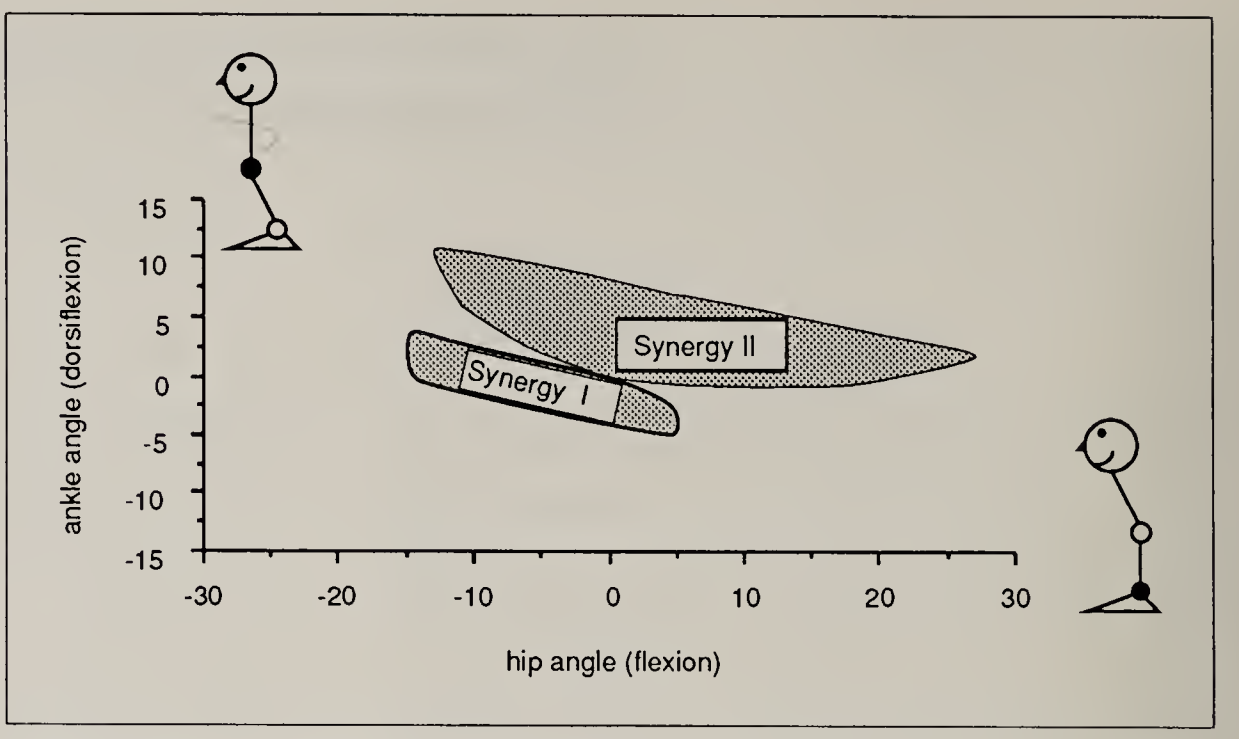

Figure 2. Regions of body positions where muscles on one side of the body (front or back) are activated to restore upright posture.

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SUPPORT

National Institutes of Health (1985-present)
National Science Foundation Fellowship Award (MEG)
VA RR&D Merit Review (1986-present)
RR&D Core Resources

Gon Khang, MS
Felix E. Zajac, PhD

A Computer Model for Control of Paraplegic Posture

PROBLEM Suitable computer models and feedback-control strategies need to be developed to study paraplegic standing controlled by functional electrical stimulation (FES).

SIGNIFICANCE Computer models can be used to design user-specific FES control systems enabling paraplegics to regain their mobility. The feedback controller thus developed can automatically regulate the body position.

BACKGROUND Although much is known regarding automatic control-system design, we still face problems to be solved in designing a control system for functinal electrical stimulation. There exists no formal method for determining a feedback control law for a nonlinear system with bounded state variables. That is, muscle forces, which are to be controlled, can be neither negative nor infinite.

Secondly, for a given muscle set, there are many different ways to stimulate them to produce the desired performance, *i.e.*, muscle redundancy. Another important consideration is muscle fatigue, which significantly affects paraplegic standing induced by electrical stimulation.

HYPOTHESIS We hypothesize that development of an automatic feedback control law is critical to FES-induced paraplegic standing and to investigation of trade-offs among alternative systems based on different design criteria.

APPROACH Our modeling efforts start with characterizing the elements which compose the overall model, *e.g.*, the relation between the electric pulse input and the muscle force (activation dynamics and musculotendon dynamics). Figure 1 shows the planar body-segmental model where we model arm motion (*e.g.*, lifting a cup or dialing a phone) as an external disturbance, assuming the arms move slowly.

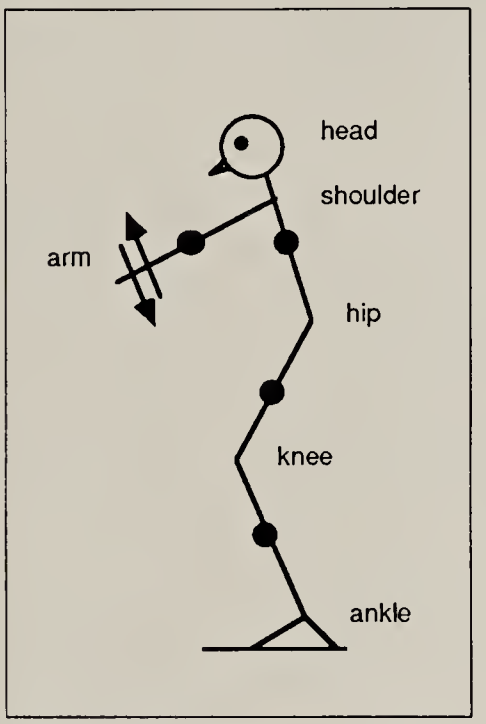

Figure 1. Planar body-segmental model.

Given a measurement strategy, we can design an output-feedback controller based on the simplified system dynamics. Our current approach is to combine muscles crossing each joint into one equivalent joint-torque actuator. The linear approximation of the system dynamics enables us to design an optimal output-feedback strategy. We decide individual activation levels in such a way that energy consumption should be minimized. Energy minimization was motivated by assuming that muscle fatigue can be lessened if one consumes as little energy as possible. Figure 2 shows a schematic block diagram for the dynamics and control. Two types of body movements are being considered: recovery of the upright position from a sitting position, and maintenance of the upright position against arm manipulation.

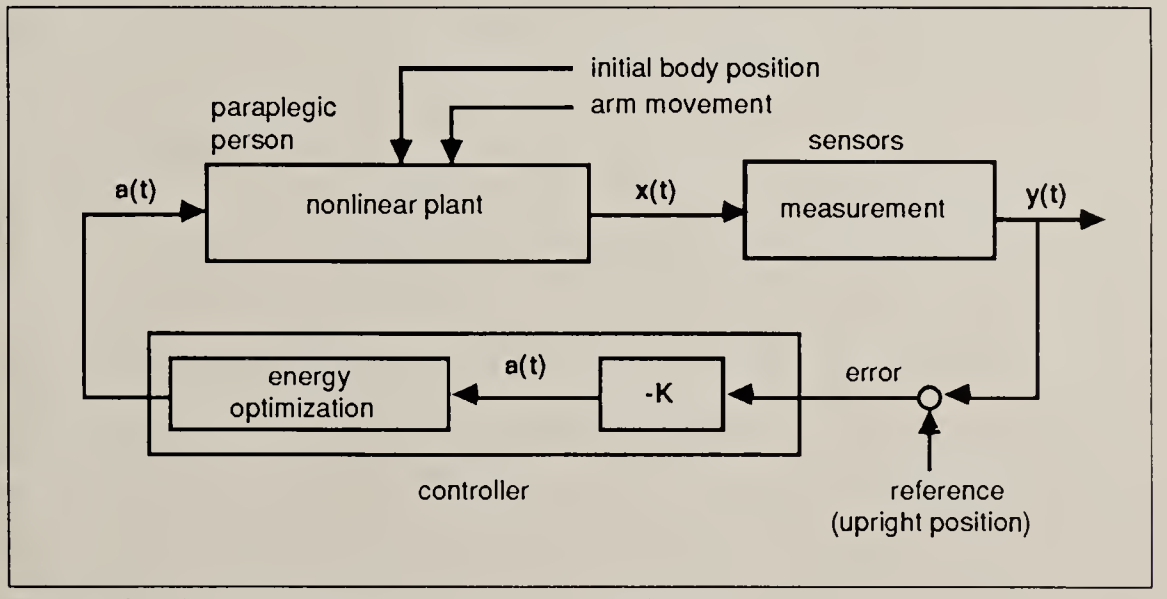

Figure 2. Block diagram for computer simulation.

STATUS We have developed reasonably complex models of activation dynamics, musculotendon dynamics and body-segmental dynamics of the human lower extremities. An output-feedback control law design based on linear approximation of the system dynamics was applied to the original nonlinear model to see how the feedback controller would function against position perturbations and arm movements. We found that the feedback controller can automatically recover and maintain the upright position, although the range of motion depends on strength of the selected muscles. We also found consistent activation patterns which should minimize energy consumption. Currently, efforts are being made to optimize the measurement strategy and to design a feedback law that can protect the user from falling.

PUBLICATIONS

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SUPPORT

VA RR&D Merit Review (1986-present)
National Institutes of Health (1985-present)
RR&D Core Resources

Gary T. Yamaguchi, SMME
Felix E. Zajac, PhD

Feasibility and Conceptual Design of Systems to Restore Natural Gait to Paraplegics

PROBLEM A significant population of spinal cord injured patients have permanently lost the ability to walk voluntarily. In most such cases, the nerves and muscles remain intact below the spinal cord lesion. Paralysis of the lower extremities occurs because the central nervous system is unable to send or receive viable locomotor controls through the lesion.

Experiments have demonstrated that reasonably controllable, although quickly fatigable, contractions may be elicited from paralyzed muscle using functional electrical stimulation (FES). Some success has already been achieved using FES to generate slow, brace-supported gaits. Although we expect improvement as our knowledge and experience with FES grows, the state of FES-assisted gait rehabilitation is constrained by the limits of available technology and clinical practice.

SIGNIFICANCE Our computer-modeling work will provide the framework for future development of realistic, realizable FES systems to restore the ability to walk to paralyzed individuals. Using computer models to simulate the effect of FES on the body, we will explore issues of practicality beyond the level of our current clinical abilities. Specifically, this study addresses the control and coordination of artificially stimulated contractions to restore gait that has a *normal* appearance.

We intend to use computer simulations to identify the medical and/or technological problems that need to be solved in order to attain this goal, as well as the physiological requirements that must be met by the reconditioned muscles themselves. The information gained will help to guide the course of further development and experimentation in FES-related research.

BACKGROUND Clinical research groups have had limited success in using FES as a means to improve locomotor skills in paralyzed individuals. To date, Bajd, Kralj, *et al.* [2] have developed postural-switching strategies enabling the best of their subjects to stand for extended periods of time using FES in conjunction with the stabilizing influence of a walker. One of their subjects is also able to ambulate regularly for 3 hours assisted by crutches, covering distances of up to 1-km. Their work has also concentrated on skin and implantable-electrode stimulation systems. Chizeck, Crago, Keith, Marsolais, Mortimer, Peckham, and others [1,3] have amassed thou-

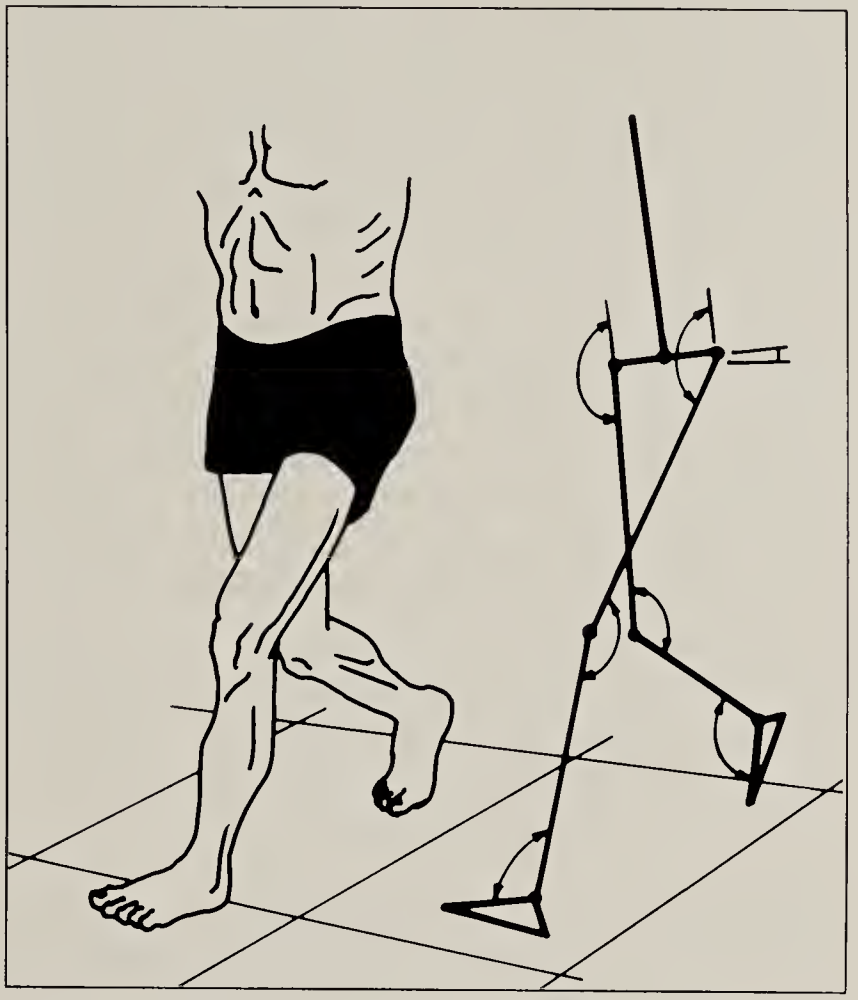

Figure 1. The idealized 8 degree-of-freedom walking model, showing assumed rigid body segments as they relate to the lower extremity.

sands of hours of experience using intramuscular coiled-wire electrodes. One of their findings indicates the need for independent stimulation of nearly all the paralyzed, and some of the voluntarily-controlled muscles in order to achieve slow, brace- and walker-assisted gaits. Baker, Campbell, McNeal, Waters, *et al.* [4] have investigated issues of controllability and endurance for electrically stimulated muscle using surface, subcutaneous, nerve cuff, epimysial, and epiphesial electrodes with a variety of stimulation parameters. Petrofsky, Phillips, *et al.* [5]

have produced startling and highly publicized results in the areas of orthotically assisted gait, cycling, and reconditioning of paralyzed muscle.

The overall approach of these and other clinical studies has been to use the best technological developments available (mechanical bracing systems, lightweight orthotics, implantable stimulating systems, etc.) and to use the most able and committed subjects in an experimental "try it and see" setting. Therefore, they are limited by the constraints of current technology and tend to focus on immediate problems at hand.

What is needed in addition to these studies is a fresh look from a global perspective, unconstrained by our current capabilities, that can answer questions such as: Is it reasonable to expect paraplegics to be able to walk normally again? What medical and technological problems must be solved in order to achieve this goal?

Our experience in modeling the musculoskeletal dynamics of lower-extremity movements will be invaluable as we investigate these issues.

HYPOTHESIS A simplified computational model of a human can be developed that will reflect the important determinants of gait (hip, knee, and ankle flexion/extension; pelvic list), and the properties of muscles, joints, and tendons. Computer simulations of gait driven by reasonable electrostimulation systems will enable us to evaluate differing locomotor control strategies, resistance to fatigue, stability and safety issues, requirements on specific muscle strength and endurance, and the like without conducting time-consuming and potentially dangerous experimentation using human subjects.

APPROACH Due to the complications introduced by the dynamics of muscle activation and the development of musculotendon force, this investigation will be undertaken in two phases. The first will specify the force-generating requirements throughout the gait cycle for selected sets of electrically stimulated muscle-tendon actuators. Once a physically realizable set of muscles has been established, the second phase will determine the pattern of stimulation required to obtain the desired forces on a muscle-by-muscle basis.

Dynamic programming will be utilized in the first phase, as it is a viable method of exploring optimal control issues on a global scale. Moreover, it is well-suited to optimal control problems of this type, in which physical limitations on both maximum muscle force and the ability to modulate force should be imposed. We hope to determine, at a coarse but physically realistic level, the pattern of muscle-tendon force that minimizes simulated deviations from a normal gait trajectory as well as energy expenditure by the muscle set.

A three-dimensional, dynamic model driven with muscle-tendon actuators will be analyzed from 12% to 62% of the gait cycle (the period when the right forefoot is on the ground). Eight degrees of freedom in the rigid-body model will allow us to examine lower limb flexion/extension at the ankle, knee, and hip, plus ab/adduction of the stance leg, without becoming unnecessarily complex.

STATUS The eight degree-of-freedom computational model has been derived, programmed, and checked through forward dynamic simulation. Dynamical equations of the model have also been incorporated with the dynamic programming algorithm. Future plans, in addition to those described above, include refinement of the cost function in order to improve the quality of the gait, comparison of different energy-conservation strategies, and examination of the functional aspects of restoring normal gait to paraplegics.

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SUPPORT

VA RR&D Merit Review (1986-present)
RR&D Core Resources

Gary T. Yamaguchi, SMME
Felix E. Zajac, PhD
Eric L. Topp, MS
Melissa G. Hoy, PhD

Computer Simulation of Knee-Joint Mechanics

PROBLEM Computer models of human motion (*e.g.* gait, jumping, cycling, etc.) require not only models of muscle and musculoskeletal geometry, but models of the joints as well. Current joint models that accurately reflect knee behavior are highly complex and computationally intensive, making them unsuitable for real-time whole-body dynamic simulations of motion.

SIGNIFICANCE The goals of this study are to determine the principal flexor/extensor mechanisms of the knee and to develop a computationally efficient knee joint model that can be incorporated into our overall dynamic system model of the lower extremity. Our efforts to develop and use such a model include the investigation of real-time computer animation as a clinical research tool. We envision realistic animation to be an informative and easily interpretable display of computer-generated data. Real-time capability extends the usefulness of this display even further, since the effects of adjusting model parameters become evident immediately. For example, such a model could be used to explore the feasibility of lower-limb functional electrical stimulation (FES) systems on a patient-by-patient basis before surgery is actually performed.

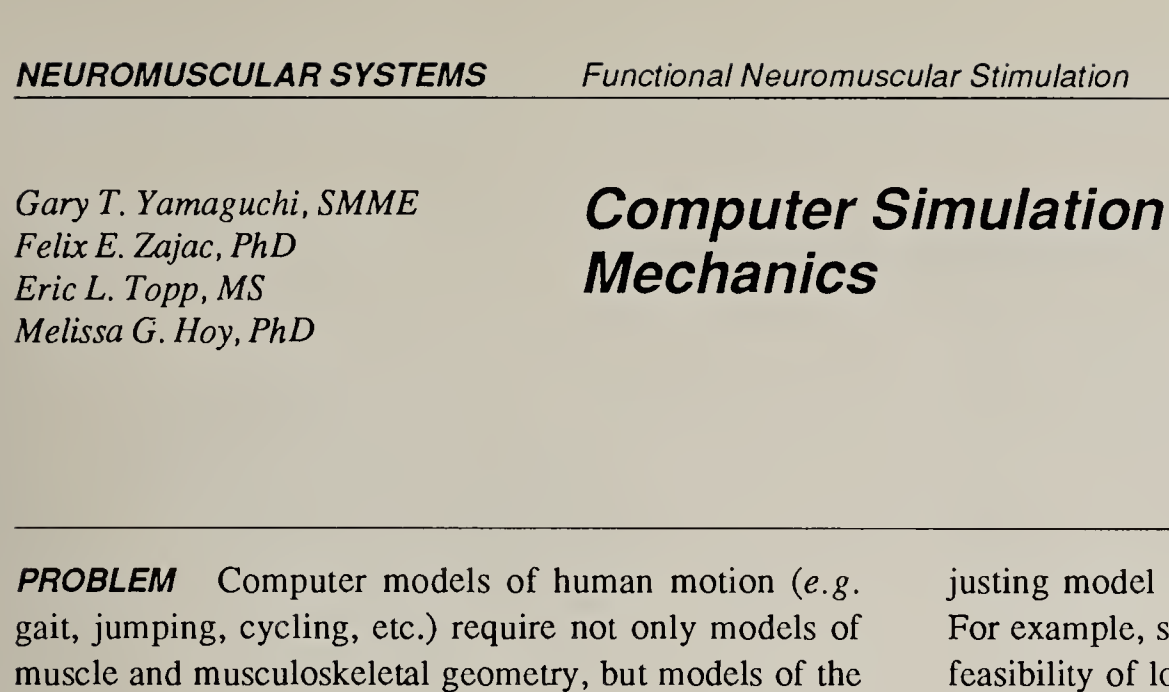

Figure 1. Tibiofemoral joint configurations may be specified by prescribing a locus of instantaneous centers of rotation (ICR). Some ICR pathways (×) from the literature cause the femur to lose contact with the tibia (A); our locus matches observed tibiofemoral contact locations (▲) with joint flexion (B). Arrow indicates insertion of patellar ligament (●).

BACKGROUND Development of lower extremity musculoskeletal computer models of mammalian movement requires an understanding of joint mechanics. In typical simulations of human gait, posture, and jumping, the knee joint is treated as a simple, two-dimensional pin joint. Yet, it has long been known that the knee acts in a much more complicated fashion. For example, numerous reports describe the contributions of articular surface geometry, movement of the instantaneous axis of tibial-femoral joint rotation, patellar mechanics, etc. Highly-detailed computational models developed by others have therefore been developed that take some of these factors into account, enabling researchers to predict joint behavior given a specific set of conditions. While some other joints behave similarly to pin joints, the knee does not; it should be described more accurately since it significantly influences human mobility.

Thus far, with our musculotendon model (see Report 14), we have used combinations of simple mechanical elements (springs, dashpots, etc.) to form a system that behaves approximately like living tissue. Such a model is needed for the knee joint as well, in order to reflect the effects of joint geometry and the mechanical levering action of the patella, and to determine the relative influence of various other joint phenomena on whole-body motions.

APPROACH A minimal set of elements composed of idealized strings, rods, and cams is used to model the lig-

aments and tendons, the patella, and the articular surfaces of the femur and tibia, respectively. A two-dimensional model is formulated in such a way as to allow independent specification of contact surface geometry, location and movement of the instant center of joint rotation as a function of knee flexion angle, patellar and patellar ligament lengths, and initial orientations. Geometric and motion constraints are imposed to prohibit unrealistic configurations and motions, such as a tendon passing through the surface of a bone. This model and these constraints will enable us to emulate published experimental data and thus determine, in essence, the mechanical operation of the joint.

STATUS A model characterizing the extensor mechanism from full extension to 90 degrees of flexion has been formulated and incorporated into our computational model of the lower extremity. Results using nominal parameter values compare well with experimental measurements reported in the literature. Sensitivity to changes in patellar thickness, length, and patellar ligament length were also explored in order to determine the influence of these parameters on patellar ligament tension, patellofemoral contact force, and the effective moment arm of the quadriceps. The model is presently being used to improve the accuracy of our simulations of human movement, and specifically, to evaluate the use of FES in lower-limb control and coordination schemes.

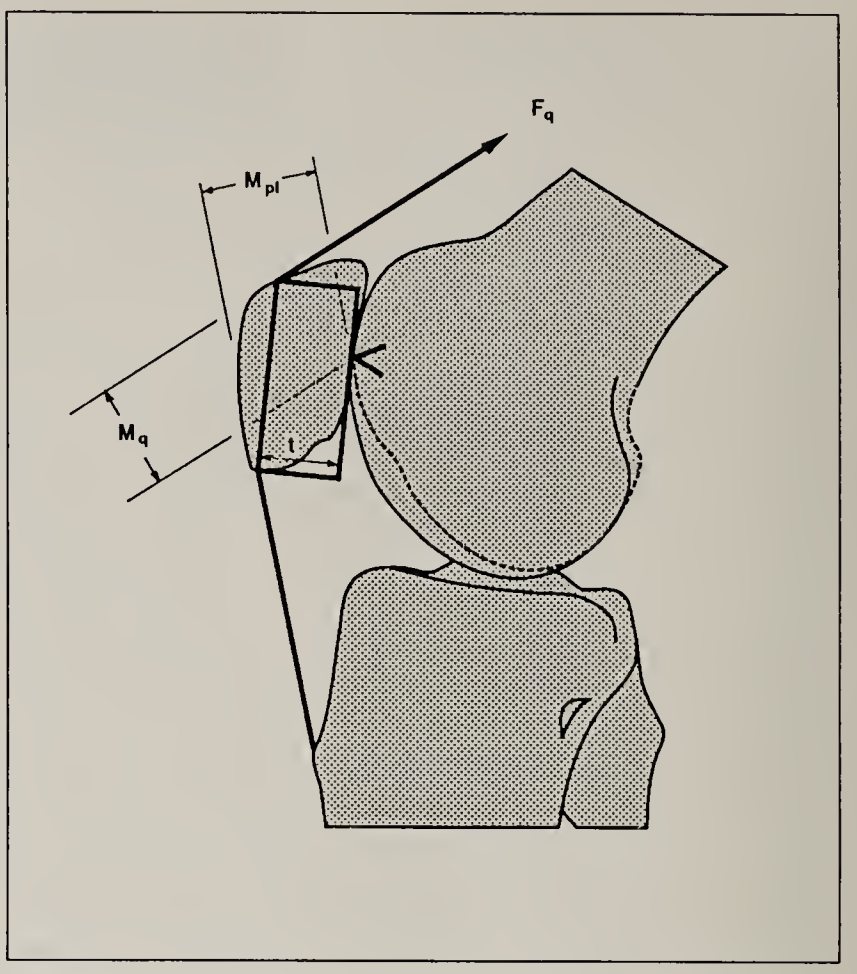

Figure 2. A rectangular block of thickness t, *incorporating the important mechanical parameters of patellar thickness and length, can be used to approximate the patella. When a force* (F_q) *is applied by the quadriceps, moments of force about the patellofemoral contact point* (<) *must be balanced to maintain static equilibrium. Thus the moment arms for the quadriceps and the patellar ligament* (M_q *and* M_{pl}, *respectively) determine the force applied to the patellar ligament through leveraging. We have found the patella's levering action to have significant effects on joint extension at flexion angles greater than 30 deg.*

PUBLICATIONS

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SUPPORT

National Institutes of Health (1985-present)
VA RR&D Merit Review
RR&D Core Resources

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Computer Graphics Display of Human Movement

PROBLEM In our studies of muscle coordination during human movement, we are often inundated with large quantities of data. To efficiently interpret these data, we need a system to easily access and visually compare them.

SIGNIFICANCE A system of displaying data clearly and conveniently is not only helpful in explaining results to others, but it is an essential part of the research process itself. The visual comparison of data is an efficient method for assessing the accuracy of our simulations and models of the human body. For example, while a simulation may stay within certain constraints of a program designed to emulate human movement, the animated "playback" of that simulation on a computer graphics system might reveal an obviously "inhuman" movement. On the other hand, if we assess a simulation to be accurate, we can use the same system to analyze the results and improve our understanding of muscle coordination.

BACKGROUND Investigators are constantly searching for methods to organize data that will help reveal fallacies in their theories, or better yet, uncover important information that can be hidden when data are presented numerically. Plots are one of the more traditional forms of data display, and the use of computers eliminates the process of plotting the data points by hand. However, obtaining plots of our data still involves some tedium which distracts from the research process. Also, there are many occasions when plots are difficult to interpret and obscure important qualities of a data set, particularly with human-movement data (*i.e.*, it is difficult to see the coordination of body-segments in a plot of the segments' trajectories). As a result, the investigator spends time learning how to read a plot that reveals only part of the desired information.

APPROACH We are developing a framework for a very friendly environment for accessing and comparing human-movement data. The user controls a screen cursor with a "mouse" to make selections from menus and to set up "windows" containing different graphical displays. We are limiting the need for keyboard input and use icons rather than words for appropriate operations (*e.g.* resizing a window). The user can watch a sequence of frames in an animated display, stop at any frame, and compare it to other windows that are stopped at the same or different points in time of the simulation (see Figure 1). Our objective is to have an interactive system for efficiently accessing and comparing data without the burden of a tedious, cryptic, and distracting computer interface.

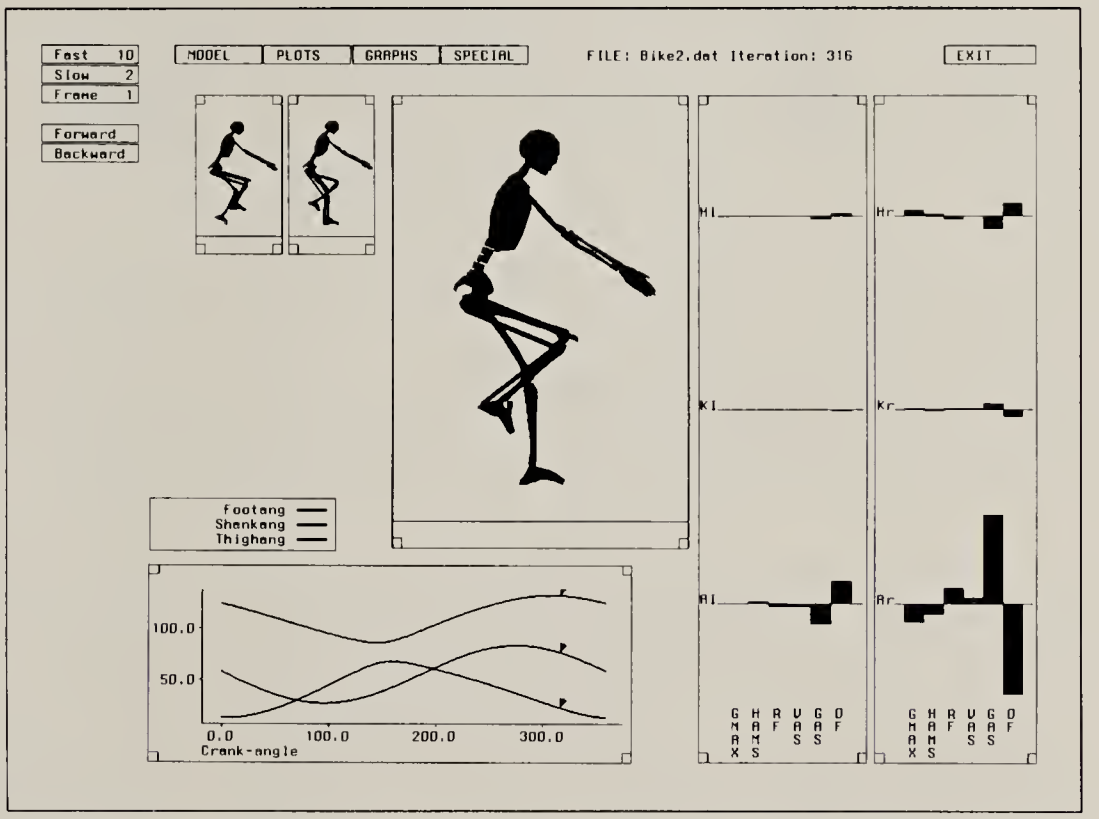

Figure 1. One frame of an animated sequence displayed with the computer graphics data-display system.

STATUS We are currently programming a Silicon Graphics IRIS 2400 computer-graphics workstation to display human movement data that is stored in or com-

puted by a VAX 11/780. Once a simulation on the VAX is complete, the investigator transfers the results to a display program residing in the IRIS. The program then sets up an environment in which the user may open different windows. There is the option of displaying several graphical formats inside the windows. One option is to display an animated musculoskeletal model. In the past, we printed or displayed a simulated movement as a series of stick figures showing the changing position of the model—a very difficult image to interpret. With animation as an option, the user sees a moving skeleton, and as the muscles are activated, they change from blue to red and glow brighter as their activation levels increase. Another option displays bargraphs to show how a selected muscle contributes to the acceleration of each joint angle or body-segment. The user also has the option of plotting in color any given set of data against any other set (*e.g.*, joint angles vs. time). As needs for other display options arise, we can easily incorporate them into the existing framework.

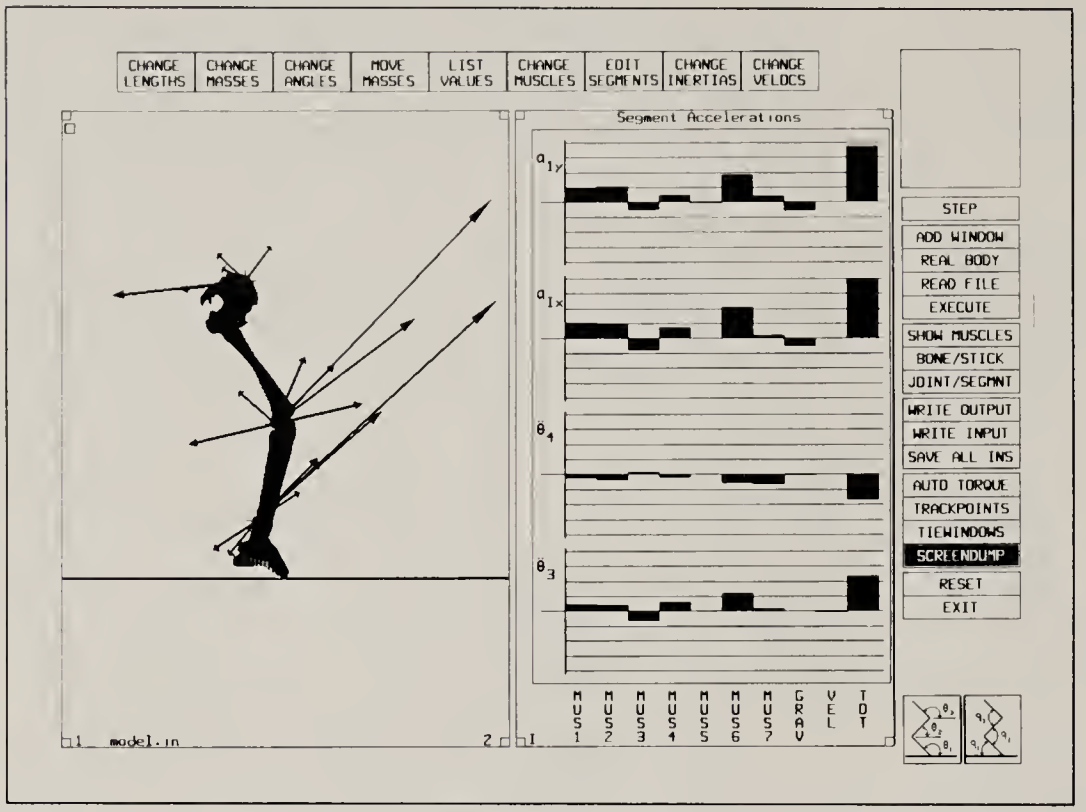

Figure 2. Typical image generated by the leg simulator. The arrows on the skeletal figure correspond to the muscle-induced linear accelerations of points on the body and are color-coded with the bargraphs and labels.

We have implemented this system as a discussion tool and to visually interpret large sets of data. Specifically, it is used to analyze data generated by computer simulations of jumping, pedaling, posture, and walking. We also use this system to interpret force and muscle electrical activity data gathered during experiments.

Presently, we are working on programs that use the graphics workstation to simulate human-movement as well as display it, so that eventually investigators can watch and manipulate the parameters of a simulation while it is running. One such program simulates movement of the human leg. Using mouse or keyboard input the investigator can specify the parameters of the mechanical system (the leg), including muscles and their forces on the body-segments. The program computes the equations of motion for this system and solves them to find each muscle's contribution to the acceleration of each body part. The results are displayed both with bargraphs and with an animated skeletal figure (see Figure 2). The investigator can use the window system to create several different leg models on the screen and analyze them simultaneously. A future version of the dynamical leg model will include our recently developed muscle model, so that the user can specify a muscle by name and have the computer calculate the appropriate muscle length and force as the system parameters change.

We have found these programs to be very helpful in communicating our ideas and results to other investigators. They have also helped us locate problems in some of our biomechanical models. We are looking towards developing a tool to combine the computing and analysis processes and thereby efficiently test our theories about the locomotion of disabled persons.

SUPPORT
National Institutes of Health (1982-present)
VA RR&D Merit Review (1986-present)
RR&D Core Resources

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Effect of Collagen Type III on Axonal Regeneration in Artificial Nerve Graft

PROBLEM In some traumatic peripheral nerve injuries, significant loss of nerve tissue may result in a gap too wide for an end-to-end anastomosis. In these cases, a nerve graft is necessary to bridge the gap. The technique currently preferred is the autograft, in which a section of one of the patient's own nerves, often the sural nerve of the foot, is used for the graft. The disadvantage of this technique is that it requires the sacrifice of a healthy nerve in order to repair the damaged one.

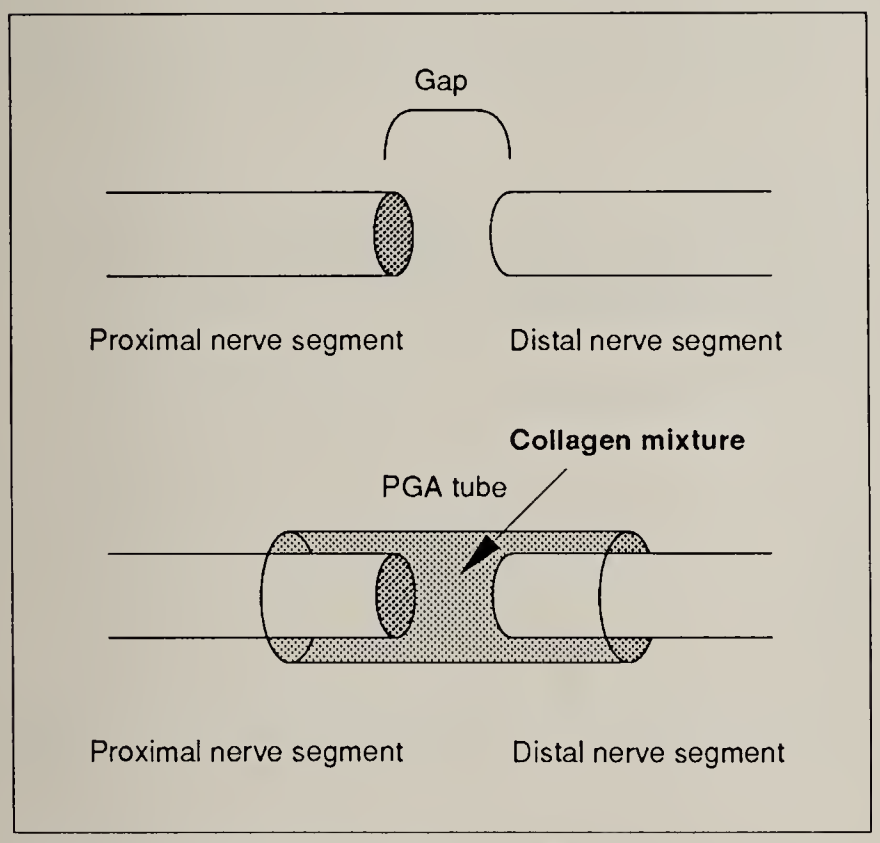

Figure 1. Artificial nerve graft.

SIGNIFICANCE An artificial nerve graft (ANG) consisting of a passive conduit filled with growth medium would be preferrable to the autograft technique. It would do away with the need to sacrifice one nerve to save another. Moreover, its characteristics could be optimized to provide better axonal regeneration and hence better functional recovery.

BACKGROUND Various types of biological tubes—arteries [9], veins [3], pseudosynovial tubes [6,7]—have been used with some success. A synthetic biodegradable tube is better because it will be resorbed leaving only the regenerated nerve, and also because it can be made available at any time, size, and quantity.

Previous work done using such a biodegradable tube made of polyglycolic acid (PGA) and filled with a hypoantigenic collagen gel (see Figure 1) has shown that axons are able to regenerate into the collagen medium, but the rate of regeneration is less than in the autograft. Therefore, we are interested to determine the factors that will enhance the rate of nerve regeneration.

The role of collagen in wound repair [8] as well as its "non-structural" functions [1] are well established. However, the role of collagen in nervous tissue repair is still unclear. Biochemical analysis of various mammalian (rat, rabbit, and monkey) peripheral nerves done in our laboratory has confirmed previous histochemical studies suggesting the selective presence of collagen type I and type III in the epineurium and the endoneurium respectively [2,5]. Other studies have shown that collagen type III is present in higher quantity in early wound repair and has higher affinity to certain substrates [4].

HYPOTHESIS This study is to determine whether the addition of collagen type III to the ANG growth medium enhances axonal regeneration.

APPROACH The first part of the study is to determine the optimal mixture of collagen type I and type III in an artificial nerve graft in the rat. In each animal, a 0.5-cm-long segment of nerve was removed from the distal transected ends of both peroneal nerves. One randomized side in each animal was repaired with an autograft using the segment removed from the opposite nerve using 10-0 nylon suture. The other side was repaired using an artificial nerve graft. The artificial nerve graft was composed of a polyglycolic acid (PGA) tube (Davis and Geck Co., Pearl River, NY) filled with a mixture of varying ratio of collagen type I and type III. The following mixture ratios were used: 100% type I, 75% type I and 25% type III, 50% type I and 50% type III, 25% type I and 75% type III, and 100% type III.

STATUS Nerve repair was done on a total of fifteen animals (three with each of the above mixture ratio). Nerve biopsies and electrophysiology were done in ten animals six to seven months post-operatively. The percentage of regeneration was estimated electrophysiologically using the integrated monophasic compound action potential (IMCAP) method. The preliminary results are summarized in Figure 2.

These preliminary results appear to indicate that collagen type III has some axonotrophic effect on axonal regeneration in an artificial nerve graft in the rat. Electrophysiology on the remaining animals and histologic correlation are crucial data needed prior to starting the second part of the study.

Mixture Ratio	%IMCAP Collagen	%IMCAP Suture	N
100% I : 0% III	42.5	35.5	2
75% I : 25% III	41.5	56.5	2
50% I : 50% III	52.0	38.3	3
25% I : 75% III	pending	pending	
0% I : 100% III	80.0	41.3	3

Figure 2. Preliminary results of artificial nerve graft with different mixtures of collagen I and III.

In the second part of the study, artificial nerve grafts, using the ideal collagen mixture determined above will be compared to sutured autografts.

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SUPPORT

VA RR&D Merit Review (1987-present)
VA Career Development Award (HNP, 1987-present)
RR&D Core Resources

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Nerve-Bundle Conduction Velocity Distributions: Clinical and Research Applications

PROBLEM Measurement of nerve conduction velocity (CV) is an important element in the electrophysiological evaluation of patients with suspected neuromuscular disorders. Conventional methods of determining nerve CV focus predominantly or exclusively upon the velocity of the fastest-conducting (largest-diameter) fibers in the nerve bundle. The properties of slower-conducting fibers (which comprise the majority of elements in the nerve bundle) are traditionally assessed only indirectly, or not at all.

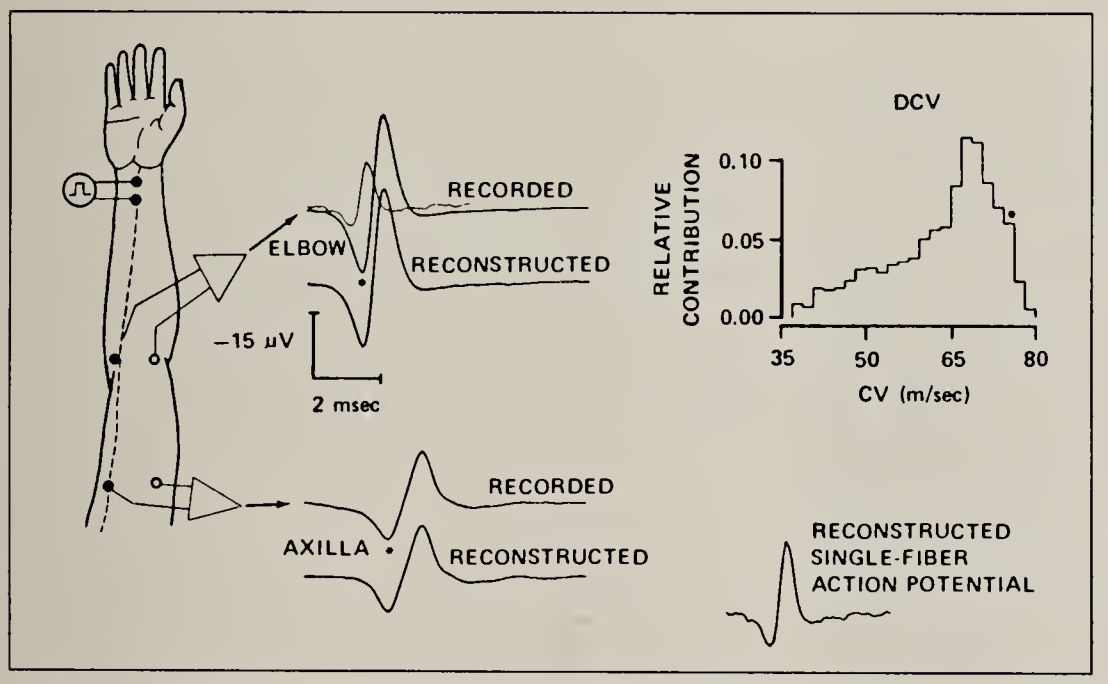

Figure 1. Elements in the derivation of the median nerve DCV in a normal subject.

SIGNIFICANCE The capability to estimate the conduction velocities of the various classes of nerve fibers comprising the nerve bundle may be expected to enhance the sensitivity and specificity of neuromuscular electrodiagnosis, to improve the functional assessment of injured nerves, and to facilitate the quantitative evaluation of therapies for nerve diseases and injuries.

BACKGROUND We have developed a computer-based method for estimating the distribution of conduction velocities (DCV) in the subpopulation of large myelinated fibers comprising human peripheral nerves. The method operates upon surface-recorded compound nerve action potentials, and is distinguished by its generality and its suitability for clinical implementation in the electroneuromyography laboratory.

HYPOTHESIS (1) That ongoing clinical trials of DCV analysis will confirm its diagnostic superiority to conventional measures of nerve CV; (2) that DCV analysis will yield insights into the pathophysiology of neuromuscular disorders and nerve injuries; (3) that DCV analysis can be implemented on existing electroneuromyographic equipment, so as to be more widely available for evaluating patients with neuromuscular disabilities.

APPROACH DCV analysis has been and continues to be applied in normal individuals, and in patients with diabetic neuropathy, nerve injury, amyotrophic lateral sclerosis, multiple sclerosis, and other conditions. The DCV findings in these individuals are compared and contrasted with those from conventional nerve CV measurements. Different methods of DCV analysis have been compared in normals and in patients. DCV analysis has been implemented on one commercial electroneuromyograph.

STATUS Nine journal articles and one book have been published. Clinical trials are ongoing and the transition into regular clinical use is underway at Stanford and at several other laboratories. DCV analysis is being applied to the study of experimental nerve repair and regeneration. Discussions are ongoing regarding commercial distribution of this technology.

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SUPPORT

Muscular Dystrophy Association
Nicolet Instrument Corporation
Kittredge Neuromuscular Fund
VA RR&D Merit Review (1981-83)
RR&D Core Resources

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Erik Valainis

Automatic Decomposition of the Electromyogram

PROBLEM The electromyographic examination plays an important role in the diagnostic evaluation of many neuromuscular disorders. It involves the use of a needle electrode to record electrical signals from a patient's muscles (see Figure 1). These signals, called electromyograms (EMGs), result from the electrical discharges of muscle fibers during muscular contraction. In current practice, most neurologists assess EMGs by watching the pattern they make on an oscilloscope screen and by listening to the way they sound, an assessment that is qualitative and subjective.

SIGNIFICANCE A quantitative method for analyzing EMG signals would provide greater objectivity, reproducibility, and diagnostic sensitivity in EMG examinations. This in turn might be expected to result in earlier and more accurate diagnosis of neuromuscular disorders, with earlier institution of specific treatment where appropriate, resulting in more favorable disease outcome with less residual disability.

BACKGROUND There have been two main approaches to quantitative EMG analysis. One approach has been to decompose the signal into its fundamental physiological components—the discharges of individual groups of muscle fibers known as motor-unit action potentials (MUAPs). The sizes and shapes of the MUAPs provide sensitive evidence about the health or pathology of the muscle fibers and their neural connections. Until recently, however, decomposition has been possible only for the relatively simple EMGs recorded during weak contractions. A second approach has been used to quantitate the more complex EMGs recorded during forceful contractions. These "interference-pattern" EMGs, so called because of their resemblance to random noise, have been characterized in statistical ways, for example by counting the number of times the signal "turns" or changes direction per second. Abnormally low or high numbers of turns have been found to be indicative of pathology. At present, no method of quantitative EMG analysis has gained wide acceptance.

HYPOTHESIS We believe that it should be possible to use computers and advanced signal-processing techniques to decompose moderately complex EMG signals into their component MUAPs.

APPROACH We have developed a method called Automatic Decomposition Electromyography (ADEMG) which is able to decompose EMG signals recorded at up to 30% of maximum contractile force and containing up to fifteen simultaneously active MUAPs (see Figure 2). The method employs several novel signal-processing steps, including a high-resolution interpolation algorithm for comparing spike shapes accurately. ADEMG is fast enough (one to two minutes processing time per 10-second EMG signal) to be practical for routine clinical use. ADEMG has been licensed to, and is now commercially available from, Nicolet Biomedical Instruments.

Figure 1. Patient undergoing an electromyographic examination of the brachial biceps.

The following steps are involved in the ADEMG method:

(1) The raw EMG signal is digitally high-pass filtered to transform the MUAPs into spikes that can be more easily detected and distinguished.

(2) The spikes are identified using a template-matching algorithm. No attempt is made to resolve superimposed spikes, so that not all spike occurrences are identified.

(3) The spike trains that correspond to valid MUAPs are verified on the basis of the regularity of their firing patterns.

(4) The MUAP waveforms are back-averaged from the raw signal using the identified spikes as triggers.

(5) The properties of the MUAPs (amplitude, duration, number of turns, firing rate) are estimated from their firing patterns and averaged waveforms.

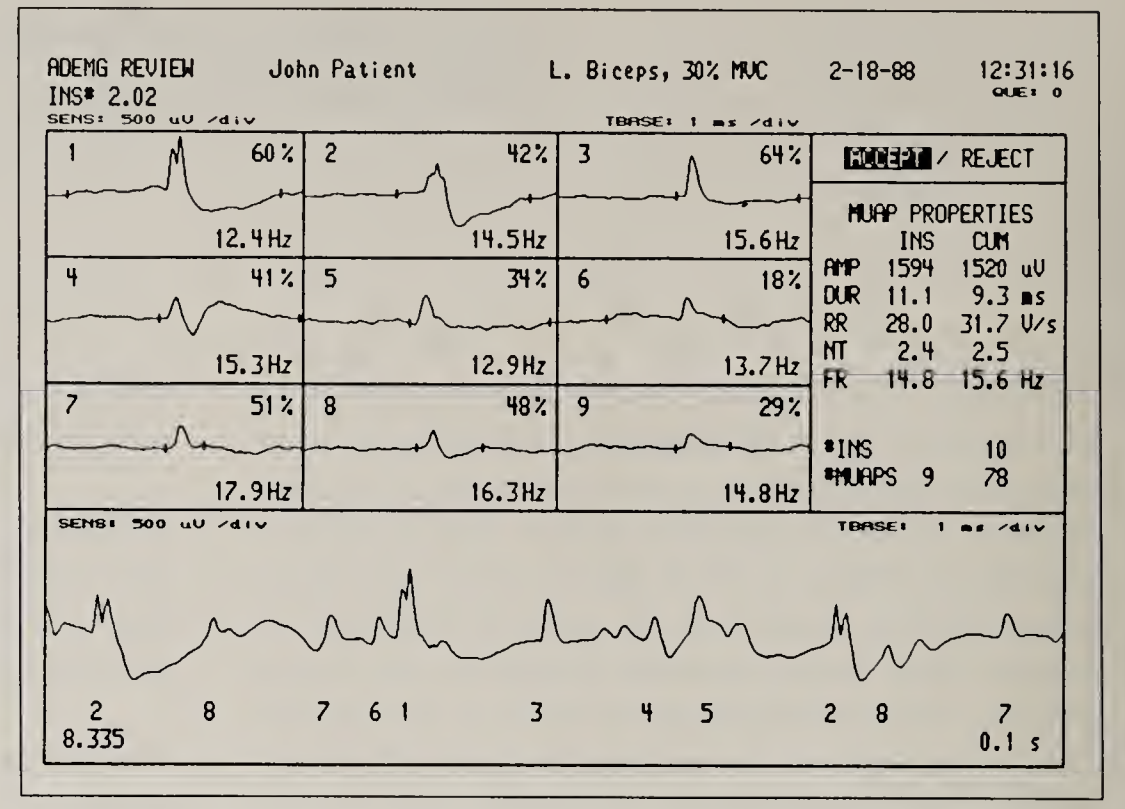

Figure 2. Example of typical decomposition obtained using the ADEMG method. The bottom trace shows a segment of EMG with several MUAPs identified. The top traces show the identified MUAPs and their firing rates. The table lists the mean MUAP property values.

STATUS We are now in the process of clinically evaluating the ADEMG method. The particular aspects of the evaluation are described in the sections that follow. They include the evaluation of ADEMG's performance by means of computer simulations (see Report 29), the collection of a database of normative MUAP properties (see Report 30), the analysis of patients with known or suspected neuromuscular disorders (see Report 31), and the investigation of EMG changes during fatigue (see Report 32). In a related project described in Report 33 we are trying to develop a non-invasive surface electrode to replace the conventional needle electrode.

ACKNOWLEDGEMENTS We would like to acknowledge Stanford students Neela Patel, Carmen Bal, John Liu, Jennifer Hill, Kalai Lau, and Stan Sze for their contributions to this project.

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SUPPORT

Kittredge Neuromuscular Fund
Zimmermann Fund
Nicolet Biomedical Instrument Corporation
VA Medical Merit Review (1985-present)
VA Career Development Program (JEH, 1987-present)
RR&D Center Resources

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Validation and Evaluation of Automatic Decomposition Electromyography

PROBLEM Automatic Decomposition Electromyography (ADEMG) is a method we developed for analyzing clinical electromyograms (EMGs) (see Report 28). ADEMG decomposes EMGs into their component motor-unit action potentials (MUAPs) and measures various properties of the MUAPs—amplitude, duration, rise rate, number of turns, and firing rate—that contain important information for the diagnosis of neuromuscular disorders. Because the EMGs that ADEMG analyzes are too complex to be analyzed by hand or by other computer programs, we have used experiments and computer simulations to validate the method and evaluate its performance and accuracy.

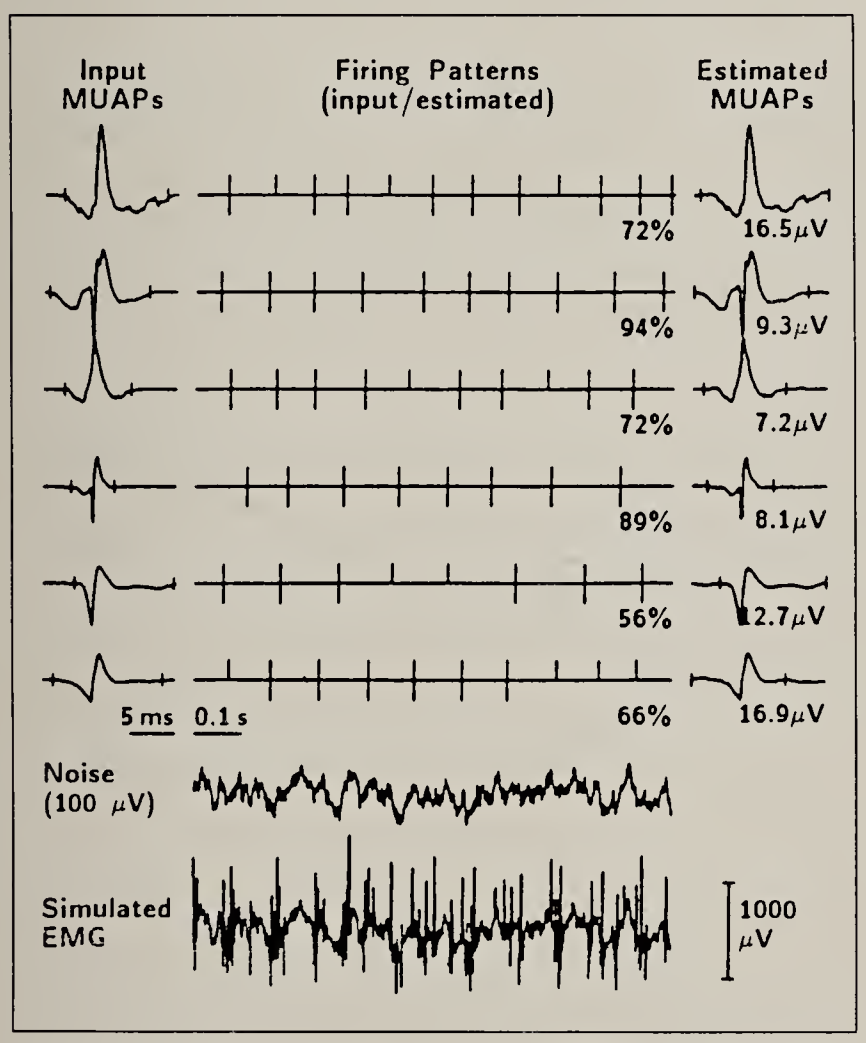

Figure 1. EMG simulation process. MUAPs from a database of actual MUAPs were combined with firing patterns and noise to simulate an EMG signal. The signal was analyzed by the ADEMG program, which decomposed it back into estimated MUAPs and firing patterns. The rms waveform error and identification rate are shown for each MUAP.

SIGNIFICANCE The ADEMG method is capable of monitoring configurational and behavioral changes in motor units that may shed important light on the cellular mechanisms associated not only with neuromuscular disorders, but with other processes such as exercise and aging as well. In order to establish the validity of such results, it is first necessary to demonstrate that the waveforms detected by ADEMG actually correspond to valid MUAPs and that the MUAP properties measured by ADEMG are accurate.

BACKGROUND We have performed two sets of experiments to verify that the waveforms extracted by ADEMG correspond to valid MUAPs. In the first set, we recorded a single MUAP during a weak contraction and showed that ADEMG could identify the same MUAP in EMGs recorded at the same site during stronger contractions. In the second set, we employed a second special electrode to independently monitor the discharges of one motor unit. The results showed that ADEMG consistently was able to identify between 33 and 98% of the firings of the monitored motor unit with few misidentifications.

HYPOTHESIS We expected that computer simulations would be an effective tool to evaluate ADEMG's performance and accuracy.

APPROACH EMGs of various complexities and noise levels were simulated as the sum of one or more MUAP trains plus random background noise (see Figure 1). The MUAPs were taken from a database of actual MUAPs of various sizes and complexities that had been recorded from healthy subjects during contractions of various forces. The simulations accurately modeled the time quantization errors that occur when actual EMGs are sampled at a rate of 10 kHz.

STATUS Two simulation studies were performed. The first study investigated the factors that affect MUAP identification and waveform estimation accuracy. The results showed that MUAP identification is hindered by increased noise, decreased MUAP rise rate, and increased interference (more MUAPs or faster firing rates). The results also showed that waveform estimation error increases with increased background noise and with decreased identification rate. The second study investigated the accuracy of ADEMG's property estimation algorithms. The results showed that MUAP amplitudes, rise rates, turns, and firing rates are estimated accurately, with standard errors of less than 2%. Duration estimates are less accurate (standard errors of up to 20%) and are negatively correlated with noise intensity, due to the difficulty in measuring MUAP onset and offset from a noisy baseline. These findings validate ADEMG's identification and estimation algorithms and point out the limitations inherent in estimating properties of MUAPs from forceful contractions.

PUBLICATIONS

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SUPPORT

VA RR&D Merit Review (1986-present)
VA Career Development Program (JEH, 1987-present)
RR&D Core Resources

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Properties of Motor-Unit Action Potentials in Normal Individuals

PROBLEM The fundamental components of the electrical signal generated by a muscle when it contracts are called motor-unit action potentials (MUAPs). The sizes, shapes, and firing rates of the MUAPs change in predictable ways in many neuromuscular disorders, and the assessment of these properties plays an important role in electrodiagnosis. However, these properties also depend on many other variables, such as which muscle is tested, the force of contraction, the patient's gender and age, and the type of recording electrode. The purpose of this project is to compile a database of information about how MUAP properties vary in normal individuals.

SIGNIFICANCE Knowledge about expected variations in MUAP properties due to muscle, force, age, gender, and type of recording electrode will improve the accuracy with which we can distinguish abnormal MUAPs from normal ones. This will make electrodiagnostic evaluations more sensitive, specific, objective, and reproducible.

BACKGROUND MUAPs arise from the electrical discharges of groups of muscle fibers, and their amplitudes, durations and shapes convey information about the health of the muscle fibers and their neural connections. MUAPs are recorded using intramuscular needle electrodes, and conventionally they are assessed by photographing them from the oscilloscope screen and then measuring their properties by hand. We have developed a computerized method for analyzing muscle signals, called ADEMG (Automatic Decomposition Electromyography, see Report 27), that now makes it possible to measure MUAP properties automatically over a range of contractile forces that was not possible before.

Although normative databases of MUAP properties have been compiled for many muscles using the conventional technique, these values are not directly comparable to those obtained by ADEMG because of a number of technical differences between the two methods. These differences include the level of contractile force at which the MUAPs are recorded, the strategy for selecting sampling sites in the muscle, the criteria for identifying MUAPs, and the criteria for measuring property values.

HYPOTHESIS We hypothesize that although the MUAP property values measured by ADEMG differ from those measured using other techniques, nevertheless they should exhibit similar trends with respect to muscle, force, age, gender, and type of electrode.

APPROACH We have used ADEMG to measure the properties (amplitude, duration, rise rate, number of turns, and firing rate) of 13,206 MUAPs from three muscles (brachial biceps, triceps, and anterior tibial) in thirty

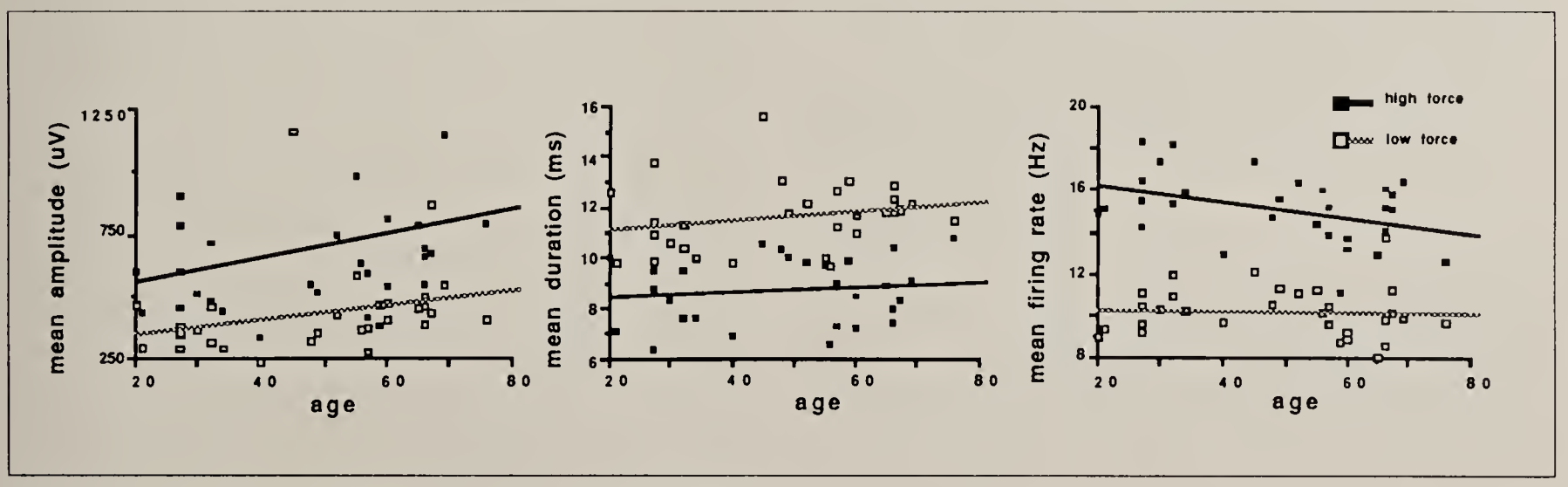

Figure 1. Normative MUAP properties for brachial biceps.

normal individuals in three age groups (20-40, 40-60, and 60-80 years). MUAPs were extracted from electromyograms recorded during stable isometric contractions at threshold, 10%, and 30% of the subject's full strength using a standard concentric needle electrode. To study the effect of the recording electrode, 7,270 more MUAPs were recorded using concentric and monopolar needle electrodes.

STATUS Illustrative results are shown in Figure 1. For the most part, specific values differed significantly from those previously reported for manually measured MUAPs. Age-related trends were consistent with previous reports, with increased age being associated with increased MUAP amplitudes, durations, and number of turns, suggesting gradual anterior horn cell loss with compensatory reinnervation. Force-related trends were also consistent with known physiological principles, with increased contractile force being associated with increased MUAP amplitudes, numbers of turns, and firing rates. Choice of electrode significantly affected MUAP amplitude and number of turns, with monopolar-recorded MUAPs being larger, confirming previous reports and theoretical analyses. All of this data has been compiled into a normative database, arranged by muscle, age group, and contractile force, which has been incorporated into the clinical ADEMG program.

PUBLICATIONS

McGill KC, Dorfman LJ. Automatic decomposition electromyography (ADEMG): validation and normative data in brachial biceps. *Electroenceph Clin Neurophysiol*, 61: 453-461, 1985.

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Howard JE, McGill KC, Dorfman LJ. Age effects on motor unit action potentials: ADEMG analysis. *Ann Neurol*, in press.

SUPPORT

Muscular Dystrophy Association
Kittredge Neuromuscular Fund
VA RR&D Merit Review (1985-present)
VA Career Development Program (JEH, 1987-present)
RR&D Core Resources

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Diagnosis of Neuromuscular Disorders Using ADEMG

PROBLEM ADEMG (Automatic Decomposition Electromyography) is a method for analyzing electromyograms (EMGs) to aid in the diagnosis of neuromuscular disorders (see Report 28). The purpose of this study is to validate ADEMG's diagnostic sensitivity by comparing the results of analyses of patients with known neuromuscular disorders against those obtained from normal individuals.

SIGNIFICANCE We expect that the ADEMG method will find wide use as a quantitative tool in diagnostic EMG evaluations, leading to greater sensitivity, specificity, objectivity, and reproducibility of these examinations. This in turn will result in earlier and more accurate diagnosis of neuromuscular disorders, with earlier institution of specific treatment where appropriate, resulting in more favorable disease outcome with less residual disability.

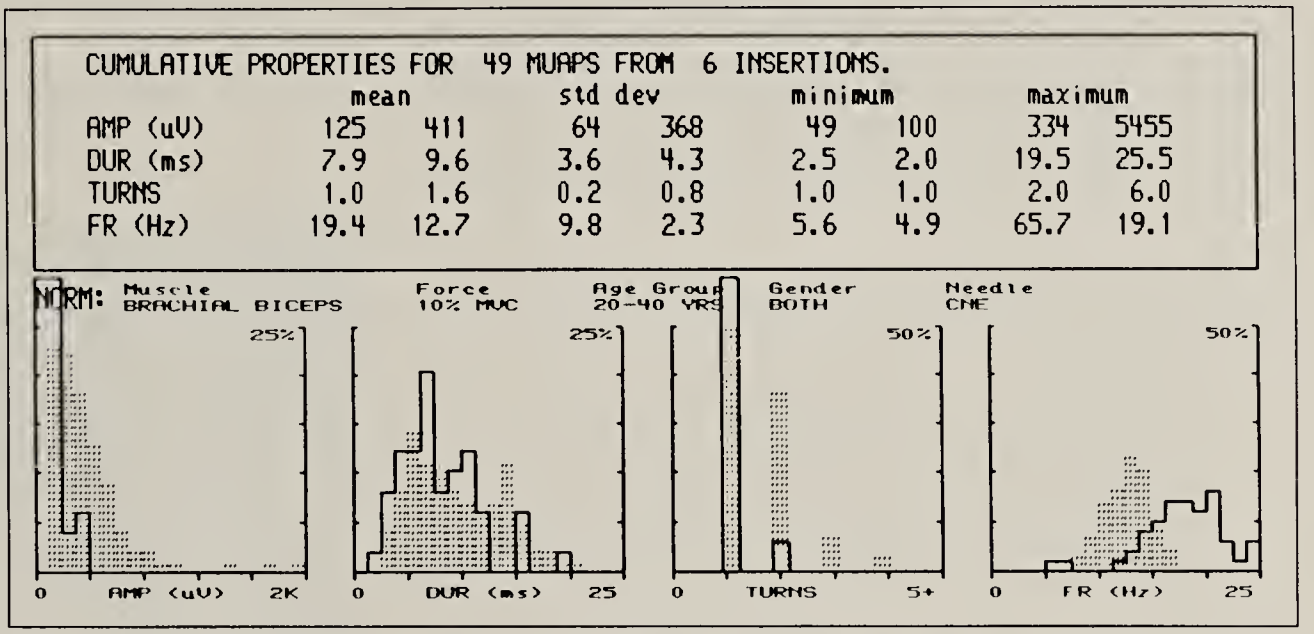
CUMULATIVE PROPERTIES FOR 49 MUAPS FROM 6 INSERTIONS.
mean std dev minimum maximum
AMP (uV) 125 411 64 368 49 100 334 5455
DUR (ms) 7.9 9.6 3.6 4.3 2.5 2.0 19.5 25.5
TURNS 1.0 1.6 0.2 0.8 1.0 1.0 2.0 6.0
FR (Hz) 19.4 12.7 9.8 2.3 5.6 4.9 65.7 19.1
NORM: Muscle BRACHIAL BICEPS
Force 10% MVC
Age Group 20-40 YRS
Gender BOTH
Needle CME
25%
25%
50%
50%
0 AMP (uV) 2K
0 DUR (ms) 25
0 TURNS 5+
0 FR (Hz) 25

Figure 1. Cumulative properties for 49 MUAPs from the brachial biceps of a 14-year-old boy with Duchenne dystrophy (solid histograms) compared with normative values (stippled histograms).

BACKGROUND Electromyograms (EMGs) are the electrical signals generated by muscle fibers during muscular contractions. They are usually recorded using a needle electrode inserted in the muscle. The fundamental component of the EMG is the motor-unit action potential (MUAP), which is the discharge of a group of muscle fibers all connected to the same nerve fiber. It has long been known that the amplitudes, durations, and complexity of the MUAPs convey diagnostically important information about the state of the muscle and nerve fibers. Small, fragmented MUAPs are indicative of muscle-fiber loss in muscle diseases such as inflammatory myopathies and muscular dystrophies; while large, long-duration MUAPs are indicative of the collateral reinnervation that accompanies motorneuron loss in neurogenic disorders such as peripheral neuropathies, amyotrophic lateral sclerosis (ALS), and traumatic nerve injuries. In the past, assessment of individual MUAPs involved the time-consuming process of manually measuring MUAP waveforms photographed from the oscilloscope screen, and was limited to the MUAPs active during very weak contractions. Our computerized ADEMG method now makes it possible to extract and measure MUAPs from EMGs generated at up 30% of a muscle's full strength quickly and automatically. ADEMG also measures MUAP firing rates, a property of potential diagnostic importance which has been virtually unstudied in the past.

HYPOTHESIS We expect that ADEMG will prove to be a sensitive and practical diagnostic tool. We think that the knowledge about later-recruited MUAPs and about MUAP firing behavior that ADEMG supplies will add to the diagnostic sensitivity of traditional quantitative EMG analysis and extend its applicability to new muscles and new disorders.

APPROACH The patient pulls against a strain gauge which displays the force as a fraction of the muscle's maximum strength. Recordings are made using a standard concentric-needle electrode inserted into the midportion of the muscle. In each muscle ten sites are sampled at each of three isometric contractile forces: threshold (limb maintained against gravity), 10% of maximum strength, and 30% of maximum strength. A 10-second EMG signal is recorded at each site. The signal is analyzed by the ADEMG program, which decomposes it into its component MUAPs and measures their amplitudes, durations, numbers of turns, and firing rates.

STATUS Ten patients have been analyzed so far, six suffering from motor neuron disease and four from muscle disease. The results agree with expected trends: increased amplitudes and durations in neurogenic disorders and decreased amplitudes in myopathic ones. The results also show dramatic increases in MUAP firing rates in myopathic disorders, a phenomenon not previously reported. Figure 1 shows illustrative results for one patient.

Future work calls for:

(1) expanding the number of patients examined by ADEMG,
(2) examining more closely the diagnostic importance of firing rate and firing rate variability,
(3) extending ADEMG analysis to the facial muscles and the anal sphincter, two muscle groups that have not been studied quantitatively in the past,
(4) testing ADEMG's diagnostic sensitivity by applying it to two subtle disease groups: female carriers of Duchenne muscular dystrophy and individuals at risk for malignant hyperthermia.

PUBLICATIONS

McGill KC, Dorfman LJ. Automatic decomposition electromyography (ADEMG): validation and normative data in brachial biceps. *Electroenceph Clin Neurophysiol*, 61: 453-461, 1985.

Dorfman LJ, Howard JE, McGill KC. Clinical studies using ADEMG in needle and surface EMG. *Computer-Aided Needle and Surface EMG and Expert Systems in Diagnosis*, Desmedt JE (ed), Elsevier, Amsterdam, in press.

SUPPORT

Kittredge Neuromuscular Fund
Muscular Dystrophy Association
VA RR&D Merit Review (1985-present)
VA Career Development Program (JEH, 1987-present)
RR&D Core Resources

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Muscular Fatigue Studied Using Automatic Decomposition Electromyography

PROBLEM As a muscle fatigues, the electrical signal or electromyogram (EMG) recorded on the surface of the skin over the muscle grows larger. The reason for this change is not known. This project is an investigation of the changes that take place during fatigue in the fundamental components of the EMG, the motor-unit action potentials (MUAPs).

SIGNIFICANCE An understanding of fatigue is important for the complete electrophysiological understanding of muscle. Such an understanding may lead to better diagnosis of metabolic disorders of muscle. It may also allow diagnoses that differentiate between the two physiological types of muscle fibers, those that are easily fatigued and those that are fatigue-resistant.

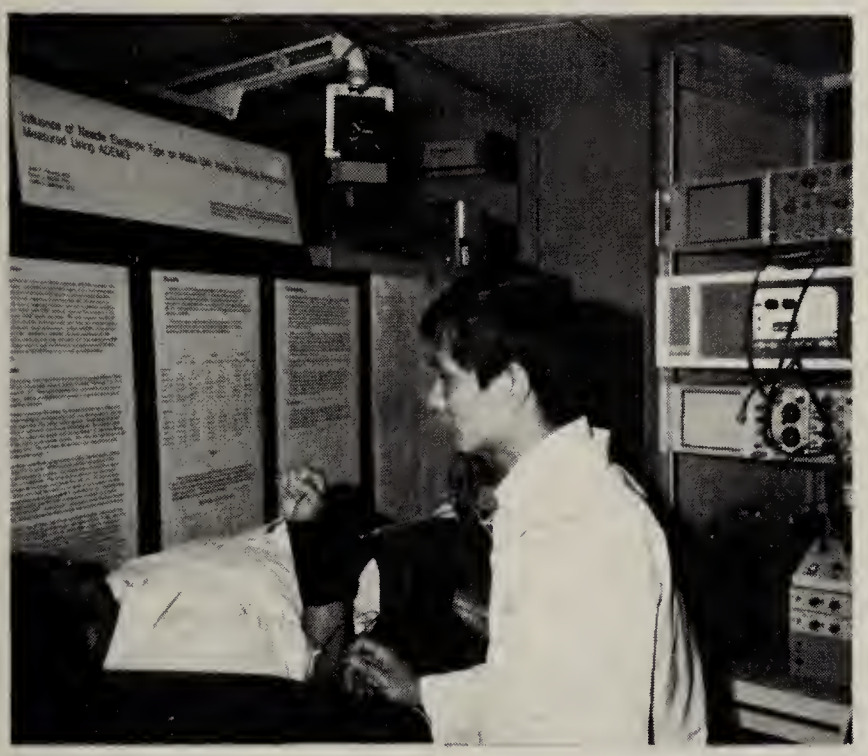

Figure 1. Fatigue study of the brachial biceps.

BACKGROUND When a muscle is required to contract forcefully for a period of time, it fatigues and becomes temporarily incapable of generating the maximum strength it had at the start of the contraction. This fatigue is due to the depletion of metabolic fuel within the muscle fibers and to the build up of waste products. Fatigue is accompanied by an increased amplitude in the gross surface EMG, which is presumably due to a decrease in muscle-fiber conduction velocity, an increase in the number of active MUAPs needed to maintain a particular force, an increase in the firing rates of the active MUAPs, and perhaps an increase in the amplitudes of the MUAPs. The precise contributions of each of these factors is not known.

HYPOTHESIS We believe that important light can be shed on the physiological changes that take place during fatigue by investigating the changes that occur in the electrical properties of the individual MUAP trains.

APPROACH EMGs will be analyzed before and after fatiguing contractions and again after a recovery period. The brachial biceps and anterior tibial muscles will be studied, and two types of fatiguing contractions will be investigated: one-minute maximal contractions, and 45-minute contractions at 15% of maximal strength. EMGs will be recorded using a needle electrode from ten sites in the muscle at two contractile forces—threshold and 30% maximum.

The EMGs will be analyzed by the ADEMG (Automatic Decomposition Electromyography) program that we have developed (see Report 28). This program will decompose the EMGs into their component MUAP trains and measure the properties of those trains, including MUAP amplitude and firing rate.

STATUS Preliminary studies have been performed for the brachial biceps in five normal subjects. The results suggest that fatigue is associated with marked increases in MUAP firing rates. Studies of ten more normal subjects and ten patients with known neuromuscular disorders are planned.

PUBLICATIONS

McGill KC, Cummins KL, Dorfman LJ. Automatic decomposition of the clinical electromyogram. *IEEE Trans Biomed Eng*, BME-32: 470-477, 1985.

McGill KC, Dorfman LJ. Automatic decomposition electromyography (ADEMG): validation and normative data in brachial biceps. *Electroenceph Clin Neurophysiol*, 61: 453-461, 1985.

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Muscular Dystrophy Association
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RR&D Core Resources

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Non-Invasive Electromyography

PROBLEM Diagnostic electromyography (EMG) is an important tool in the evaluation of patients with known or suspected neuromuscular injuries or diseases. Most clinical applications of diagnostic EMG require that data be collected using intramuscular needle electrodes. The procedure is invasive and painful, and it is not well tolerated by all patients.

SIGNIFICANCE The purpose of this project is to investigate new methods for recording and analyzing EMG signals non-invasively. A non-invasive EMG examination would be an important clinical advancement for several reasons. First, it would make it easier for the electromyographer to obtain the cooperation of the patient. This would enable more thorough examinations of sensitive muscles, such as those of the face and hands, of patients with low pain tolerance, and of children, who are often not examined at all now using needles. Second, it would facilitate serial EMG monitoring, for example, of response to therapy for neuromuscular disability. Third, it would allow examination of some muscles, such as the intercostal muscles of the chest, that are usually not examined using needles for fear of perforating underlying vital structures.

Figure 1. Prototype noninvasive EMG electrode.

BACKGROUND Surface EMG recordings have generally been considered unsuitable for electrodiagnosis, even of superficially situated muscles, because of the attenuation and distortion suffered by the myoelectric signals as they pass through the subcutaneous tissues and the skin. Recently, however, new types of surface electrodes have been developed that are capable of detecting the fundamental electrophysiological components of the EMG signal—the discharges of individual groups of muscle fibers known as motor-unit action potentials (MUAPs). These electrodes consist of arrays of very small (1-mm diameter), very closely spaced (2.5–5.0 mm) metal contacts, or closely spaced needles that penetrate only the outermost layer of the skin. The signals recorded by the various contacts can be combined in such a way as to accentuate the more superficial MUAPs while suppressing the deeper ones.

HYPOTHESIS We predict that computer-based signal-processing techniques can be used to decompose surface-recorded EMGs into their component MUAP trains, and that these surface MUAPs will be shown to contain information relevant to neuromuscular diagnosis and evaluation.

APPROACH EMG signals will be recorded from the skin surface by an array of small contacts. Signals from adjacent contacts will be subtracted to accentuate the MUAPs. The signals will be decomposed into trains of individual MUAPs using a modified version of our ADEMG program (a program originally developed to analyze needle-recorded EMGs, see Report 28). The ability to record the MUAP waveform at many points on the skin surface simultaneously will allow estimation of properties that cannot be easily measured using needle electrodes, including the size and conduction velocity of the motor unit and the location and spatial extent of the motor endplate.

STATUS We have developed a prototype hand-held surface EMG electrode (see Figure 1) whose features include detachable heads for either flat or needle-type contact arrays, a metal shield to ground the electromyographer and suppress noise, and an on-board buffer amplifier. Figure 2 shows two EMG signals recorded simultaneously from two locations on the hand (abductor pollicis brevis) during a moderate contraction. The signals were analyzed by the ADEMG program, and three MUAPs were identified along with their firing patterns and conduction velocities.

Future plans call for refinement of the prototype electrode, optimization of the analysis program, and development of algorithms for estimating motor-unit anatomical properties from multiple surface recordings. Our eventual goal is to develop a system for whole-muscle mapping that will consist of a large electrode with many contacts, a multichannel recording system, and a multichannel analysis program.

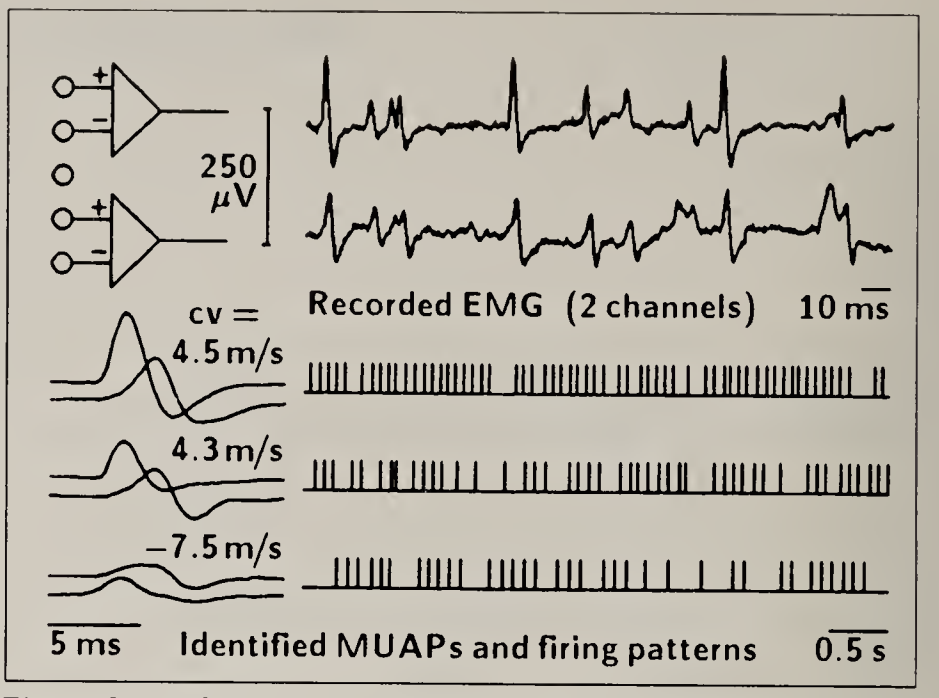

Figure 2. EMG signals recorded by surface electrodes decomposed into their component MUAP trains.

PUBLICATIONS

McGill KC, Cummins KL, and Dorfman LJ. Automatic decomposition of the clinical electromyogram. *IEEE Trans Biomed Eng*, BME-32: 470-477, 1985.

McGill KC, Dorfman LJ, Howard JE, and Valainis EV. Decomposition analysis of the surface electromyogram. *Proc Ninth Ann Conf IEEE Eng Med Biol Soc*, 2001-2003, 1987.

SUPPORT

Muscular Dystrophy Association
VA Career Development Program (JEH, 1987-present)
RR&D Core Resources

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A Smart Trigger for Real-Time Neuroelectric Spike Classification

PROBLEM Physiologists and neurologists record neuroelectric signals from muscle, nerve, and brain in order to study the way these systems work and to diagnose neuromuscular disorders. Neuroelectric signals often contain action potentials or "spikes" arising from more than one cell. In order to study the behavior of the individual cells, it is necessary to sort out the spikes. Some applications demand that this sorting be done with high accuracy in real time.

SIGNIFICANCE Important applications for a high-performance real-time spike classifier include basic electrophysiology, single-fiber electromyography (SFEMG), and functional neuromuscular stimulation (FNS). In basic electrophysiology, such a device would make studies of cellular behavior easier and more accurate. In SFEMG—a technique for diagnosing neuromuscular disorders in which a selective needle electrode is used to observe the discharges of individual muscle fibers—such a device would make the SFEMG examination less technically difficult and more practical for widespread use. In FNS, such a device could be used to derive control signals for a prosthesis or paralyzed muscle from the discharges of individual motor units in an intact muscle. Presumably these control signals would reflect the user's intentions more sensitively than signals derived from gross surface EMG.

BACKGROUND At present, spikes can be sorted in real time by an electronic device called a window discriminator, or they can be sorted off-line by computer. Window discriminators are fairly simple and hence somewhat intractable and simple-minded: they require careful hand tuning, have difficulty distinguishing similarly shaped spikes, are sensitive to changes in spike shape, and give unsatisfactory results if more than two or three spike trains are present. Computer analysis, on the other hand, can achieve excellent sorting performance by bringing sophisticated signal-processing algorithms to bear. However, up until now, computer analysis has been too slow for real-time use.

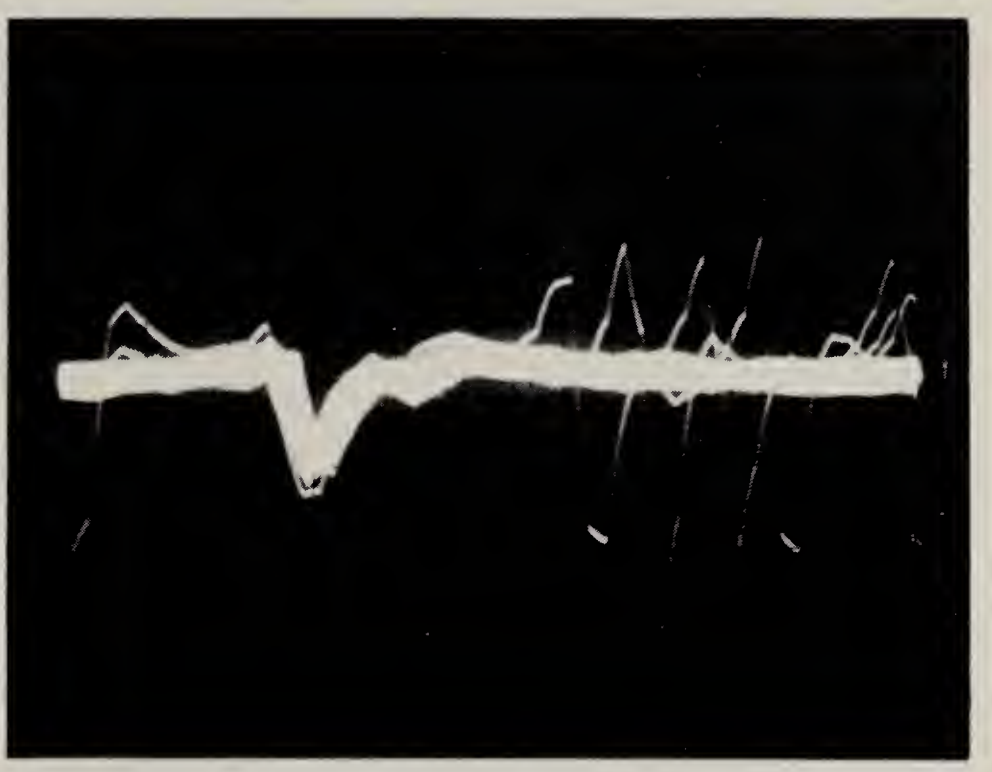

Figure 1. Single-fiber EMG signal triggered by the Smart Trigger (duration = 20 ms).

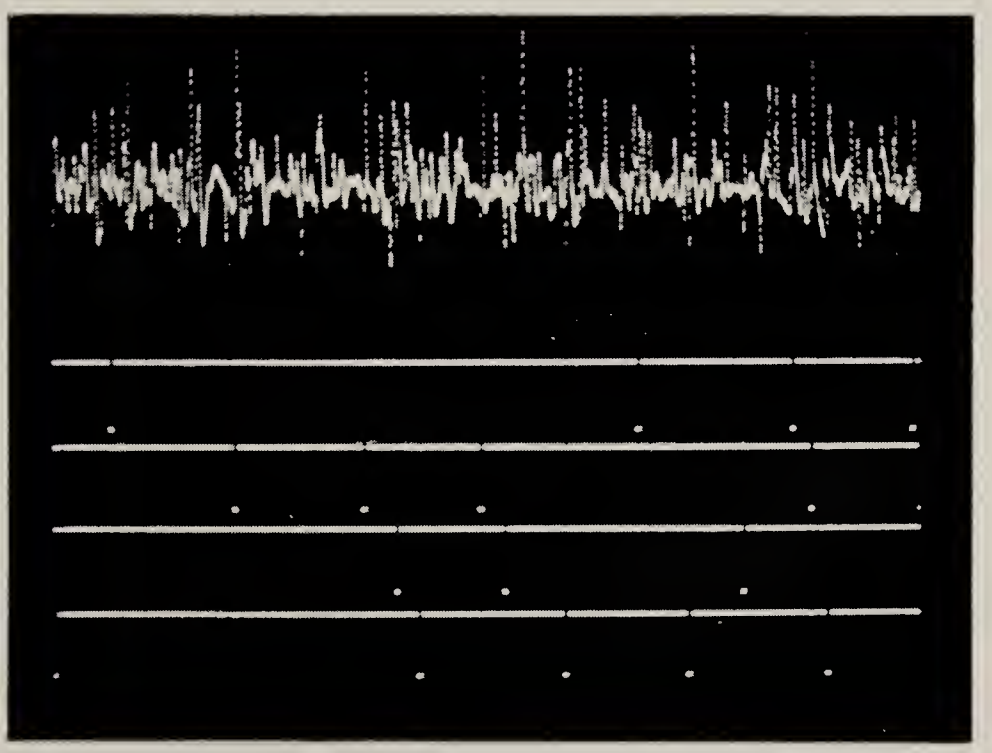

Figure 2. Concentric electrode EMG signal and four Smart Trigger output channels (duration = 0.5 s).

1. Carnegie-Mellon University

HYPOTHESIS We felt that it should be possible to build an inexpensive, high-performance, real-time spike trigger by implementing powerful signal-processing algorithms for spike detection and discrimination on a fast microprocessor. We expect that such a device will find useful applications in electrophysiology and electrodiagnosis.

APPROACH We have designed a spike classifier, which we call the Smart Trigger, that can automatically discriminate up to eight different spike waveforms on a single input channel. The Smart Trigger uses a template matching method to identify all the spikes in the input signal (or its first or second time derivative) that exceed a detection threshold. (Differentiation often improves triggering performance by flattening the signal baseline and sharpening the spikes). The templates are formed from the spikes of recurring units, and they are constantly updated to track slow changes in spike shape. An interpolation algorithm is used to achieve high temporal resolution in spike/template comparisons in order to minimize time quantization errors.

STATUS We have built a prototype Smart Trigger that uses an M68000 microprocessor and two TMS32010 digital signal processors. It can sample at a rate between 1 and 20 kHz, and can handle signals containing over 200 spikes per second. Trigger pulses are delivered on eight output lines corresponding to eight identified units, or on a single line on which the user can select any one of the units. Figures 1 and 2 demonstrate some of the Smart Trigger's capabilities. Figure 1 shows several traces of an SFEMG signal triggered on the spike in the center. Figure 2 shows a segment of electromyogram and four trigger channels containing pulses marking the firings of four distinct spikes.

Future plans call for the development of three important applications of the Smart Trigger: obtaining motor-unit recruitment and firing information for diagnosis of neuromuscular disorders, measuring neuromuscular jitter in SFEMG recordings, and deriving control signals for prosetheses and FNS. These applications are discussed more fully in Report 35.

PUBLICATIONS

McGill KC, Dorfman LJ. High-resolution alignment of sampled waveforms. *IEEE Trans Biomed Eng*, BME-31: 462-468, 1984.

McGill KC, Dorfman LJ. Automatic decomposition of the clinical electromyogram. *IEEE Trans Biomed Eng*, BME-32: 470-477, 1985.

McGill KC, McMillan KL. A smart trigger for real-time spike classification, *Proc Eighth Ann Conf IEEE Eng Med Biol Soc*, 275-278, 1986.

SUPPORT

VA RR&D Merit Review (1985-1987)
RR&D Core Resources

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Applications of the Smart Trigger in Clinical Neurophysiology

PROBLEM We have developed a device called the "Smart Trigger" which now makes it possible to decompose myoelectric signals into their fundamental components in real time. This capability opens up several important new applications in clinical neurophysiology and rehabilitation.

SIGNIFICANCE One application for the Smart Trigger is quantitative electrophysiological diagnosis of neuromuscular disorders, which would result in greater sensitivity, objectivity, and reproducibility of neurological diagnostic evaluations. Another application is an improved method for controlling prostheses, which might be more reliable, deft, and non-fatiguing than present controllers.

BACKGROUND The electrophysiological assessment of muscle function plays an important role in the evaluation of neuromuscular diseases and injuries. The fundamental organizational subunit of the neuromuscular system is the *motor unit*, which consists of the group of muscle fibers activated by a single motorneuron. The electrical discharges of the motor units that accompany muscular contraction, known as motor-unit action potentials (MUAPs), can be recorded using needle or surface electrodes. The sizes and shapes of the MUAPs convey information about the health or pathology of the muscle fibers and the motorneuron, and the firing behavior of the MUAPs conveys information about the spinal and supraspinal processes that control muscular activation. Individual MUAPs are difficult to analyze in practice since signals recorded from muscle are usually very complex, with MUAP trains from many different motor units overlapping and interfering with one another.

Myoelectric signals are also used in the control of prostheses and functional neuromuscular stimulation (FNS). The patient, in order to actuate the prosthesis or to control the stimulation of a paralyzed muscle, contracts a muscle over which he or she has control. The contraction is monitored by analyzing the myoelectric signals generated by the muscle and recorded by electrodes on the skin surface. Most myoelectric controllers can produce only simple on/off control signals because the random nature of the myoelectric signal and the variations in the electrode impedance make it difficult to estimate the patient's intent more precisely.

Our Smart Trigger now makes it possible to sort out individual MUAPs and obtain information about their firing behaviors in real time (see Report 34). The Smart Trigger can be used to overcome many of the difficulties associated with electrodiagnosis and myoelectric control.

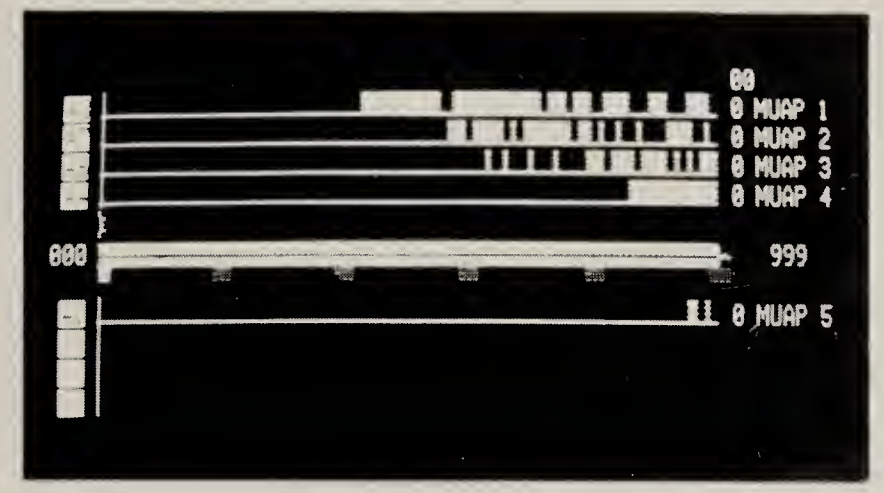

Figure 1. Output of Smart Trigger showing successive recruitment of five motor units during an increasing isometric contraction of the brachial biceps (time scale =10 s).

HYPOTHESIS We hypothesize: (1) That some disorders of the motor cortex, descending spinal pathways, and ventral horn result in irregularities of motor unit firing behavior that can be detected using the Smart Trigger. (2) That the Smart Trigger can be used to facilitate other electrophysiological evaluations such as the measurement of jitter at the neuromuscular junction. (3) That the Smart Trigger can be used to derive useful control signals for prostheses and FNS based on the observed discharge patterns of individual MUAPs. The digital nature of the MUAP firing patterns will make this type of control more accurate and less sensitive to interface changes than conventional myoelectric controllers that use surface EMG.

APPROACH We intend: (1) To develop a quantitative method for diagnosis of neuromuscular disorders based

1. Carnegie-Mellon University

on the analysis of the recruitment and firing properties of motor units. This will involve developing and validating algorithms for estimating firing related properties from the signals recorded by the Smart Trigger during low-force dynamic contractions. (2) To implement a system for single-fiber EMG analysis based on the Smart Trigger and compare its accuracy and ease of use with more conventional single-fiber EMG analysis systems. (3) To devise a method of myoelectric control in which the Smart Trigger is used to estimate the user's intent by analyzing the firing patterns of individual motor units (see Figure 1).

STATUS A first prototype of the Smart Trigger has been built. Its operation has been verified by comparison with an off-line spike-sorting computer program, and it has been successfully tested in the application of single-fiber EMG. A second version of the Smart Trigger that will be able to interface directly with other electrophysiological test equipment has been designed. Further development of the applications described here awaits VA Merit Review funding.

PUBLICATIONS

McGill KC, McMillan KL. A smart trigger for real-time spike classification. *Proc Eighth Ann Conf IEEE Eng Med Biol Soc*, 275-278, 1986.

SUPPORT

RR&D Core Resources

REPORTS

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Human-Machine Integration Program

The Human-Machine Integration Program is dedicated to the development of tools that augment the functional independence of physically limited people. While our projects are not typically directed towards changing an individual's physiological status, we are concerned with reducing the handicap often associated with disability. Emphasis is placed on functional restoration rather than anatomical correction.

Projects fall into three main areas:

(1) application of robotics technology to manipulation and mobility devices,
(2) application of artificial intelligence and linguistics to communication aids, and
(3) harnessing of human power for wheeled mobility, upper-limb prostheses, and recreation.

In addition, we are applying modern technology and computer-aided design methods to other practical problems relating to spinal and head injuries. Specifically we are developing new techniques and preventative devices for detecting or dealing with the prevention of pressure sores and the safe transport of head injury or spinal injury patients.

During the past two years, the HuMac program has invested heavily in computer aided engineering (CAE), design (CAD) and manufacturing (CAM). These tools are needed for successful completion of the complex class of interdisciplinary projects typically found in our program. They also facilitate transfer of our technology facturing, since CAD/CAM data can be sent directly to potential manufacturers for evaluation and for automatic control of manufacturing machine tools. Microcomputer technology continues to be a key ingredient in "smart" assistive devices capable of adapting to their environment and to user requirements. Increasingly, artificial intelligence methods have found a niche in our projects.

However, technology considerations remain secondary to formal identification and characterization of human needs, as well as social and environmental constraints. Will individuals with different disabilities find the product useful? Will non-disabled users also benefit from its existence to the extent that the largest possible market may be cultivated to achieve the lowest possible end-user cost?

To this end, we work hard to integrate product development and product evaluation. Formal procedures are used to obtain early user feedback on device prototypes. Though difficult to obtain, user feedback at this formative stage in the evolution of an assistive device can have a profound effect on the direction and content of R&D. Most importantly, when the product is ready, we know who needs it, who will prescribe it, and who will buy it. In the near future, we can expect that an integral technology-transfer program will achieve full programmatic status to help take advantage of recent legislation allowing cooperative R&D contracts between our Center and private companies.

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Desktop and Mobile Robots for the Severely Disabled: an Overview

PROBLEM Persons with severe physical limitations must still sense and control their surroundings to fulfill medical, daily living, and professional needs. If unable to accomplish these tasks on their own, then attendants or devices must be made available. While human attendant performance is limited by the cost, compatibility, and reliability of qualified individuals, the performance of assistive devices is limited only by available technology.

Having successfully demonstrated the potential of Desktop Vocational Assistant Robots (DeVARs), we are now faced with the problem of extending the working range of these assistant robots by making them mobile (MoVARs). We are also engaged in testing DeVAR utility in real-world situations by taking them out of the clinic and into the workplaces and homes of disabled veterans.

SIGNIFICANCE To the potential user community, the need for smart manipulation assistants is clear. Reduced dependency on human attendant care is perceived to be very desirable, not only economically, but from the point of view of privacy and independence during normal daily and vocational activities. In particular, it is very desirable to support these people in the development of employment opportunities.

BACKGROUND Since the Robotics Project's start in 1980 (see Figure 1), we have demonstrated the feasibility of voice control of a desktop robot. A robust software and hardware environment has been created from industrially proven hardware and software components. Using a Westinghouse/Unimation PUMA-260 manipulator since 1983, our assistant robots have undergone significant evolution. Through a continuing series of clinical evaluations, the Desktop and Mobile Vocational Assistant Robots have emerged as robust, clinically proven devices.

Advanced sensory systems and natural robot language interface research have begun to extend the range of operation of these robots. In particular, the Desktop and Mobile Vocational Assistant Robots will be ready for "field trials" in mid-1988. Whereas the Desktop Vocational Assistant Robot is fully ready for commercial distribution, the MoVAR omnidirectional mobile robot is just now emerging as a commercially viable system. It uses the same industrial robot arm as the Desktop Assist-

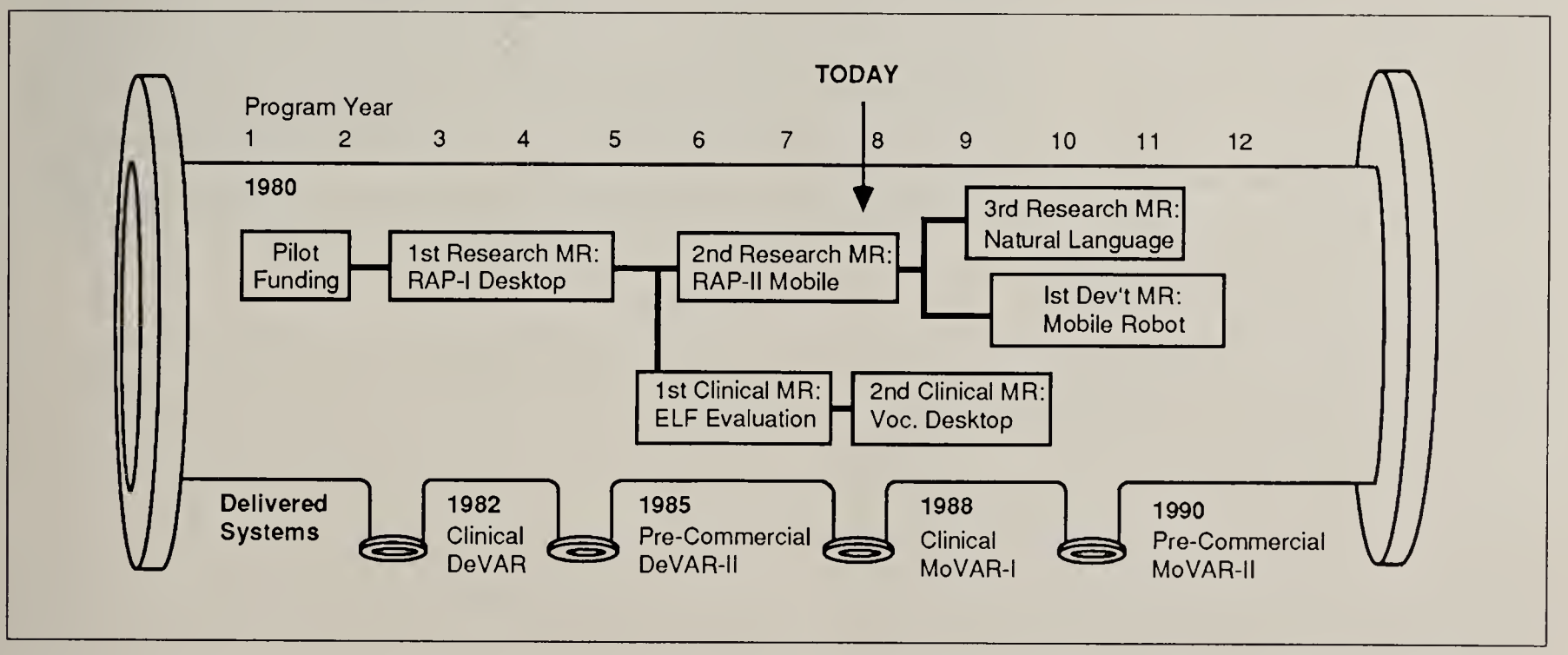

Figure 1. Pipeline model of the VA robotics project showing milestones and deliverables: 1981 to 1989 (projected).

ant Robot and shares many of the same hardware and software components for the human interface to control the robot.

HYPOTHESIS It is hypothesized that industrial robotics technology can be adapted to the manipulation needs of severely impaired veterans. First-order economic studies suggest that assistant robots can be economically successful at the same time that they bring an unprecedented degree of independence to persons with severe disability.

APPROACH We have chosen to use the best, not always the cheapest, of industrial robotics technology to serve the disabled. Manipulation in largely unstructured human habitats is typically more challenging than in comparable industrial situations. Technically, rehabilitation robotics is most like space robotics in terms of the user interface and the requirement for reliability and ease of use under conditions of long-term stress. Our strategy calls for the development of desktop robots for workstation-specific applications and mobile assistant robots for more general, spatially distributed tasks such as those found in the home and some vocational settings.

STATUS The Desktop Vocational Assistant Robot is currently being tested clinically with quadriplegic users in the Spinal Cord Injury Center of the Palo Alto VA. Several reports in this section outline the clinical results and the development process. The system contains a PUMA-260 arm and its controller which is in communication with an IBM-PC/AT computer for the user interface. The PC is programmed in a high-level programming language, TurboPascal, to coordinate all aspects of the use of the robot. The PC communicates with the user through a color graphics screen and a VOTAN voice recognition and digitized voice output system. There is an environmental controller, accessible by voice, to activate appliances and lights as well as the robot itself.

During the past year, over 20 high-quadriplegic patients have been subjects in our studies to assess the robot's performance and the quality of the interface. This feedback, as well as suggestions for applications in home and work environments, is the subject of Report 42.

The status of the mobile system is reviewed in Report 43. We have terminated the research phase for the first model of this system and are "hardening" the configuration for extended field studies. The research-prototype nature of the existing system will give way to a pre-production prototype during this development phase. The new system is expected to work reliably in clinical trials without the continuous presence of project engineering staff.

Research is proceeding on development of a natural-language interface to our mobile system (see Reports 47 and 48). We have demonstrated the feasibility of using Artificial Intelligence techniques to allow the user to command the robot using normal English sentences. This is a first step in reducing the user workload by providing full access to the robot's capabilities without requiring the user to have any computer programmer skills. Previously, the only approach dealing with "ease of use" has been to simplify the actions of the robot and to standardize its environment. Now we are putting the burden on the computer to understand the user's commands in a language natural to people.

During the next two years we will concentrate on two major objectives. First, the DeVAR is being readied for field trials as a vocational workstation. The system will be placed with a quadriplegic programmer in a local company to assess its usefulness for office manipulation tasks such as handling mail, opening manuals, and working with computer print-outs. Second, the mobile system will begin clinical trials at the VA Spinal Cord Injury Center at the conclusion of the 1988 development phase. It will then benefit from the same assessment and application programming effort that has prepared the Desktop Robot for field trials.

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SUPPORT

VA RR&D Merit Review (1981-present)
RR&D Core Resources

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Design of a Third-Generation Desktop Robotic Assistant for Daily Living Tasks

PROBLEM An important issue in giving quadriplegics control over their environment is allowing them the ability to accomplish everyday personal care tasks independently. This project is concerned with designing a desktop workstation incorporating a voice-controlled robotic aid for accomplishing activities of daily living (ADLs), *i.e.*, basic eating and hygiene tasks.

SIGNIFICANCE Enabling quadriplegics to carry out ADLs independently will give them much greater freedom to control their own daily schedules, particularly with regard to eating. It may also reduce their need for constant attendant care, with a corresponding cost savings. Also, the basic design concepts underlying the ADL workstation could be applied to the robotic aid for use in other settings, such as a vocational environment.

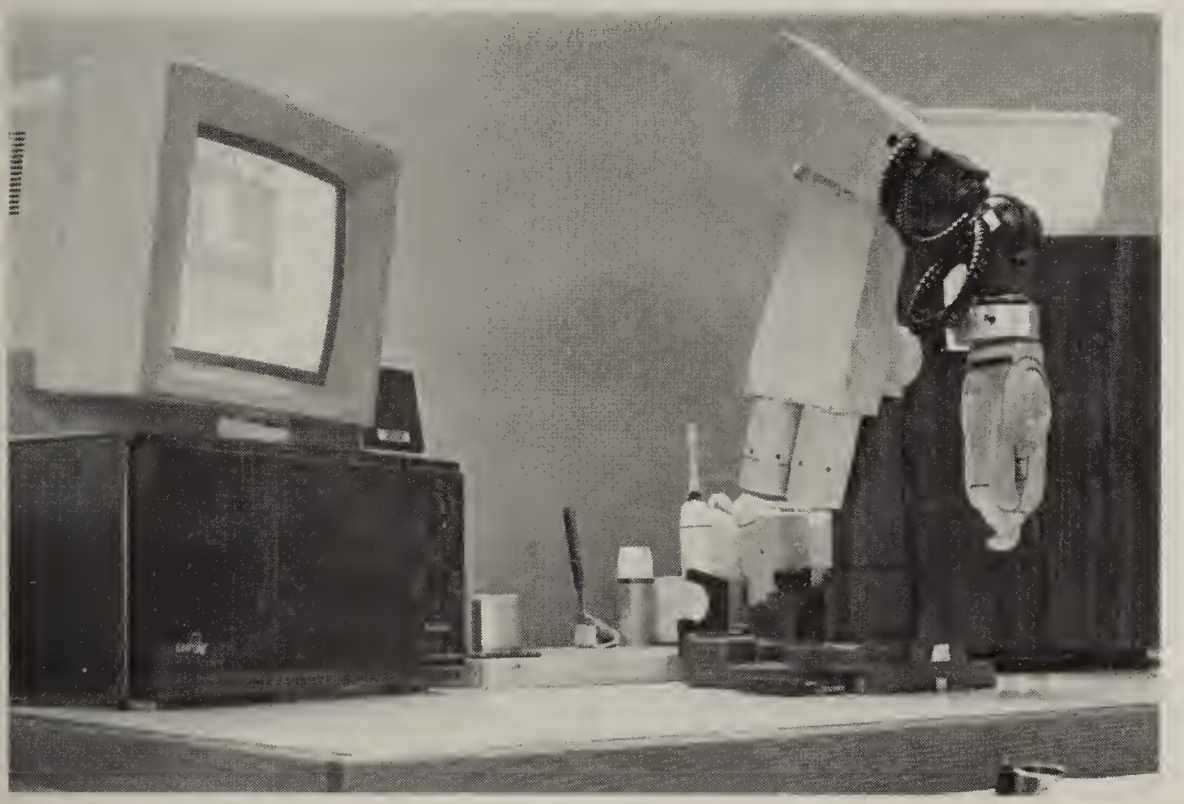

Figure 1. The Robotic-Assistant workstation for ADL tasks.

BACKGROUND The Robotic Assistant is a voice-controlled robotic arm that a disabled person can command to perform simple tasks. During the past five years, a great deal of information has been collected about the abilities of the Robotic Assistant to accomplish ADL tasks. Using knowledge gathered from the first two evaluation prototypes of the Robotic Assistant, we designed a production prototype workstation with new software and fixtures so that the robot could reliably execute tasks that would significantly enhance the independence of the quadriplegic user.

HYPOTHESIS A workstation designed specifically to accomplish certain ADL tasks should enable a quadriplegic user to carry them out efficiently and reliably. In particular, the earlier designs of the workstation were intended in part as experimental test-beds to see which tasks the robotic aid was able to accomplish. One of our main objectives in designing the third generation system was to demonstrate that the Robotic Assistant is ready to move out of the laboratory and become a viable commercial product. Using information gained from the earlier prototypes, we redesigned the robotic aid to be more "clean", compact, and aesthetic so that users would find it more acceptable for home use.

APPROACH We designed the ADL workstation to fit on a 6-ft x 3-ft table top (see Figure 1). It consists of a PUMA 260 industrial robot, a small refrigerator and microwave oven, and a wooden stand behind the robot to hold the utensils for the ADLs (see Figure 2). The workstation currently supports the following ADLs :

- Tooth-Brushing
- Face-Washing
- Shaving (with electric razor)
- Retrieving food from the refrigerator

- Heating food in the microwave oven
- Serving drinks from the refrigerator
- Feeding the user with a standard, unmodified spoon or fork

A great deal of useful feedback on the design was obtained by demonstrating it to potential users during its development and testing.

STATUS The actual construction of the workstation was completed by mid-summer 1987. Testing of the design by quadriplegic users is still ongoing. So far, the workstation has been tested by twenty different users. Results from these trials indicate that we have successfully achieved our goals of making the workstation reliable and significantly faster in completing tasks in comparison with the older designs. A survey of the disabled users who tested the system indicated that a large majority of them believed that it would be useful for accomplishing ADLs in their own homes [1].

Figure 2. Robotic Assistant performing tooth brushing (dental hygiene) task.

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Lees D, Crigler B, Van der Loos M, Leifer L. Design of a second generation desk-top robotic aid. *Proc 10th Ann Conf Rehabilitation Engineering (RESNA)*, San Jose, CA, 1987.

SUPPORT

VA RR&D Merit Review (1981-present)
RR&D Core Resources

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Design of Control and User Interface Software for a Third-Generation Desktop Robotic Assistant

PROBLEM The Stanford/VA robotic assistant is a voice-controlled robotic arm that severely disabled individuals can use to perform basic eating and hygiene tasks. It can be a powerful tool for enhancing the independence of disabled users, but only if they can learn how to operate it effectively. Thus, the user interface is a vital component of the robotic assistant's design.

SIGNIFICANCE Most users of the robotic assistant have no advanced computer training, so it is very important that its user interface allow it to be operated as easily as possible. A good user interface will enable disabled users to perform useful tasks with the robotic assistant with only a small amount of specialized training

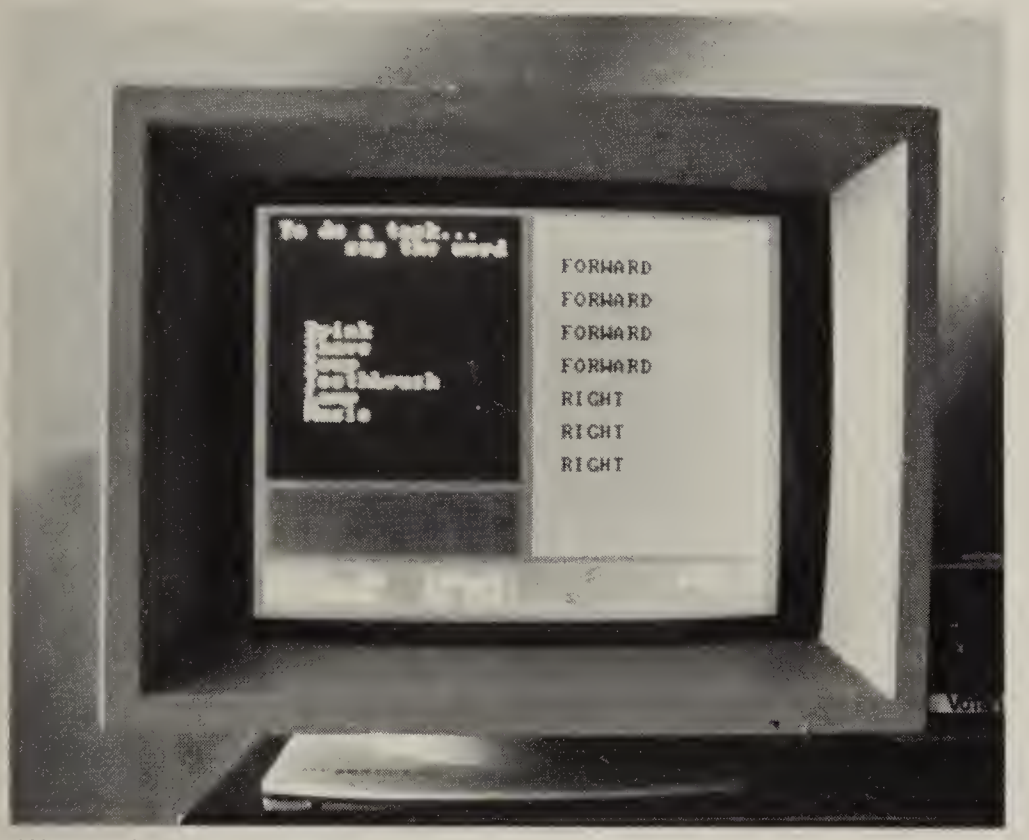

Figure 1. User interface for Robotic Assistant.

BACKGROUND The VA/Stanford robotic assistant project was conceived in 1981. Its ultimate goal is to develop a robotic assistant that can be controlled by severely disabled individuals to provide functional restoration of lost motor skills. The first generation of the robotic assistant incorporated a PUMA 250 robot controlled by a ZILOG Z-80 microcomputer. It performed functional tasks at a fairly low level, but it demonstrated the utility of a voice controlled robot.

Most of the problems with that system arose from the limitations of the hardware and software available at the time. Speech recognition and visual and speech feedback were poor by current standards. In addition, the words used as commands had to be chosen to maximize the likelihood that they would be recognized correctly by the speech recognition system, rather than for a meaningful association with the task that the robot was performing. Our goal was to incorporate improvements in computer and speech recognition technology into a new workstation with a library of pre-programmed tasks, more sophisticated controller logic, and an improved user interface.

HYPOTHESIS We believe that a successful user interface should incorporate command words that are meaningful for the task at hand, along with on-screen prompts of those commands most likely to be needed to complete the task at hand. The control program must also incorporate safety features to guard against commands that might have dangerous consequences, while still leaving the user the flexibility to accomplish useful actions that we had not anticipated.

APPROACH The user interface software was programmed in Turbo Pascal, a programming environment that allows significantly faster software development than any language available when the first generation system was designed.

Our design has three main features that make it easy to use. As described above, vocabulary was chosen to be as straightforward as possible. Tasks are initiated by name (*e.g.*, toothbrush) and motion commands for the arm are given with respect to the user (*e.g.*, left, right, up, down, etc.). Each command issued to the robot is "spoken" back to the user by the speech synthesizer. The

previous ten commands are also shown on a color display screen for the user's information. This feedback is very useful for ensuring that the voice system has correctly recognized a command. Finally, the color display prompts the user with a list of possible commands for the next step in the task being executed. The prompting display changes dynamically as the task progresses.

In addition, a number of safety features are included: ensuring that the robot always operates at a slow speed and moves in short incremental steps when it is near the user's face, verifying complicated or potentially hazardous commands (*e.g.*, opening the robot's hand) with the user to guard against misrecognitions by the voice system, and preventing the initiation of conflicting tasks (*e.g.*, dropping a glass in mid-air to pick up the fork). Finally, the control program has the ability to store a history of the user's commands, with a time stamp and information about the robot's status. This is very useful to the project staff for studying the system's performance and the user's control of the robot.

STATUS Our experience with the new robotic assistant indicates that improvements in computer and speech recognition technology in the past five years have allowed a tremendous improvement in the capability of the clinical robot system. These improvements have allowed us to use a much more intuitive vocabulary—one picked more for user comprehension than to ease the job of the voice recognition system. The tremendous increase in microcomputer power available at a reasonable price has allowed us to implement a much more sophisticated control program, which greatly reduces the time needed to learn to use the system.

The end result of these improvements is that disabled users can now learn to accomplish activities of daily living in approximately two to three hours of training. With the first-generation system, reaching a comparable level of ability would have required seven or eight hours of training. Ongoing work includes integrating a telephone and environmental control unit into the system, simplifying the procedure for training new vocabulary for voice recognition, and adding new tasks to the robot so that the robotic assistant will be easy to set-up and expand, as well as easy to use.

PUBLICATIONS

Lees D, Crigler B, Van der Loos M, Leifer L. Design of a second generation desk-top robotic aid. *Proc 10th Ann Conf Rehabilitation Engineering (RESNA)*, San Jose, CA, 1987.

SUPPORT

VA RR&D Merit Review (1981-present)
RR&D Core Resources

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Technology Transfer to the Johns Hopkins University Applied Physics Laboratory Robotic Aid

PROBLEM The VA Rehabilitation Evaluation Unit (REU) in Baltimore, MD, expressed interest in improving the user interface for a robotic aid developed at the Johns Hopkins University Applied Physics Laboratory (JHU/APL)[1]. The Palo Alto VA Robotic Assistant project was asked to determine the feasibility of adapting its user interface to the JHU/APL robotic aid.

SIGNIFICANCE The REU is interested in placing the JHU/APL robotic aid at evaluation sites, but feels that it needs some improvement upon its current (chin-controlled) user interface. It is hoped that the Palo Alto VA Desktop Vocational Assistant Robot's (DeVAR) voice-control and prompting-display system will greatly improve the ease-of-use of the JHU/APL robot.

BACKGROUND The Robotic Aid projects at the Palo Alto VA and at Johns Hopkins have evolved independently since they began. (The JHU project was begun in 1976, the Palo Alto project in 1981.) This report summarizes the results of the first effort to combine elements of the work done on these two projects.

HYPOTHESIS Based on a meeting in Baltimore in July, 1987, we concluded that it should be possible to implement the DeVAR voice interface on the JHU/APL robot with some modifications to both systems. There were certain features that could not be implemented due to the significant differences between the JHU/APL robot and the PUMA 260 robot that is used in the DeVAR. In particular, the JHU/APL arm does not implement straight-line motions (*e.g.*, left, right, up, down) which are used in the DeVAR system to position utensils (spoon, shaver, etc.) where the user can reach them easily.

Since implementing this function on the JHU/APL arm would require major hardware revisions, we did not attempt to do it. Positioning the JHU/APL arm requires issuing separate commands for each joint in the arm (*e.g.*, shoulder, elbow, wrist, etc.) to position the hand where it is desired. This feature is also available on DeVAR, but it is not extensively used by operators.

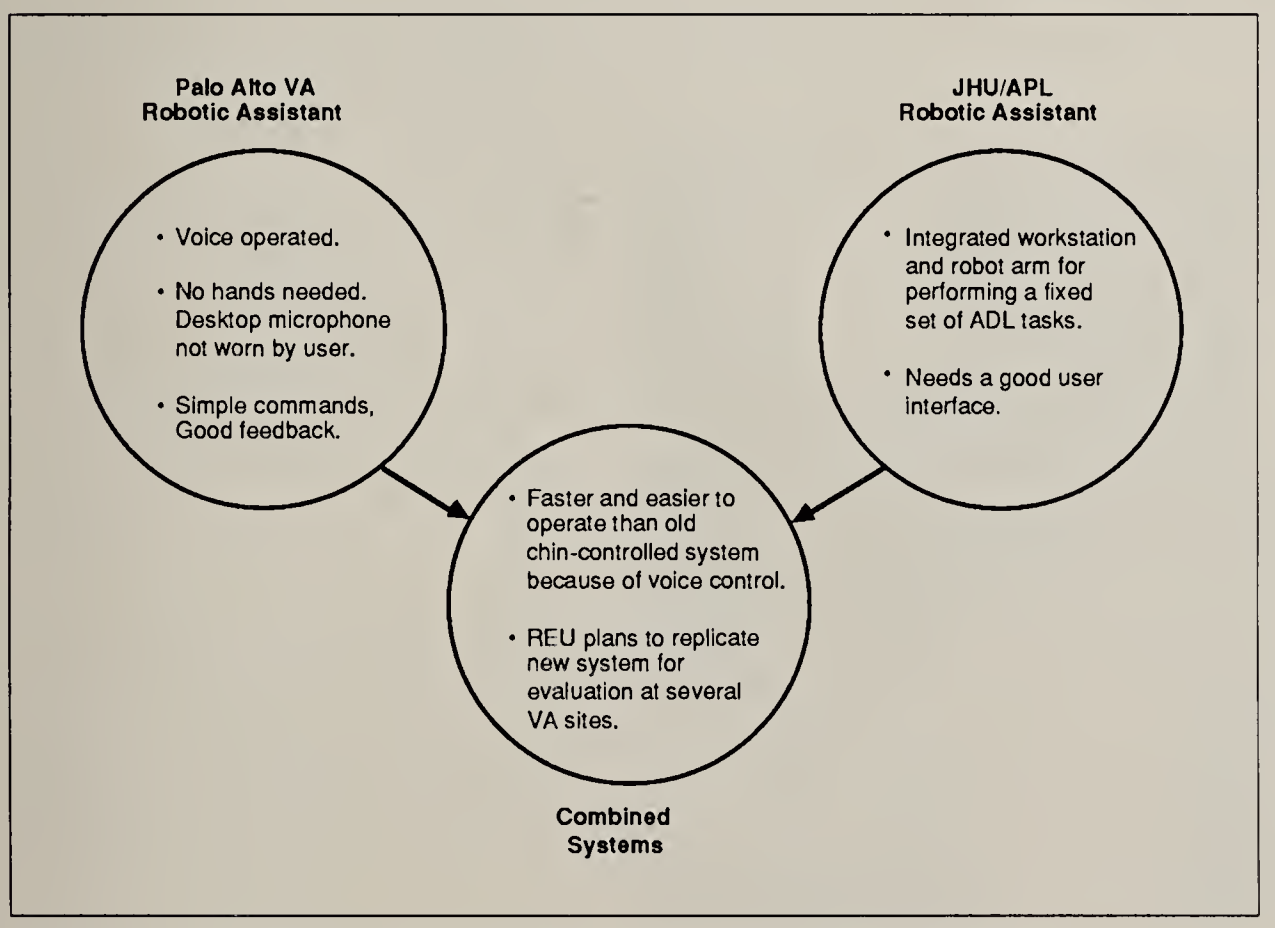
Palo Alto VA
Robotic Assistant
• Voice operated.
• No hands needed. Desktop microphone not worn by user.
• Simple commands, Good feedback.
JHU/APL
Robotic Assistant
• Integrated workstation and robot arm for performing a fixed set of ADL tasks.
• Needs a good user interface.
• Faster and easier to operate than old chin-controlled system because of voice control.
• REU plans to replicate new system for evaluation at several VA sites.
Combined
Systems

Figure 1. Combining technology from APL and PAVA robotic assistants.

APPROACH In the last half of September 1987 an intensive effort was undertaken at APL to adapt the DeVAR user interface to the JHU/APL robotic aid. With the exception of the hardware limitations mentioned above, the system performed extremely well. We were able to control motions of the individual joints in the arm and initiate complex tasks (*e.g.*, retrieving a magazine) with voice commands.

STATUS As a result of the successful demonstration of voice control for the JHU/APL robot, the REU is currently soliciting bids from manufacturers to produce several copies of the system for evaluation.

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PUBLICATIONS

Lees D, Crigler B, Van der Loos M, Leifer L. Design of a second generation desk-top robotic aid, *Proc 10th Ann Conf Rehabilitation Technology (RESNA)*, San Jose, California, 1987.

SUPPORT

Applied Physics Laboratory, Johns Hopkins University
VA RR&D Merit Review (1981-present)
VA Evaluation Unit (1987-present)
RR&D Core Resources

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Clinical Evaluation of a Desktop Robotic Aid for Severely Physically Disabled Individuals

PROBLEM The use of robotic aids by the severely disabled to perform activities of daily living (ADLs) is relatively new. Few studies have practical applications of robotics in health care. The purpose of this study is to demonstrate the reliability and performance of a third-generation robotic system that is being considered for placement in home and vocational settings.

SIGNIFICANCE Robotics technology has the potential to give severely disabled individuals maximal control and independence in performing daily activities. In addition to decreasing their dependence on human attendants for the performance of daily maintenance activities, robotics technology also offers the disabled the opportunity to become successfully, independently employed in the community. This functional independence will not only significantly decrease the cost of long term health care, but will also enhance the disabled individual's quality of life.

BACKGROUND Clinical evaluations by severely disabled individuals revealed that improvements were needed in the reliability, efficiency and safety of the first- and second-generation robotic aids. Based on these findings, the robotic system was upgraded by incorporating new tasks, modifying existing ones, and enhancing the user interface. The result was a third-generation robotic workstation, DeVAR (Desktop Vocational Assistant Robot).

HYPOTHESIS It is hypothesized that extensive evaluation of the DeVAR system by disabled users will yield valid, quantitative data that demonstrates the practicality of robotic aids for severely disabled individuals.

APPROACH This study is part of a continuing research project to investigate the use of robotic technology by disabled individuals. DeVAR employs a Unimation PUMA-260 industrial arm controlled by an IBM-PC/AT computer and operated by user commands through a VOTAN voice recognition unit. Prior robotic workstations used a standing, rotating kiosk to house supplies needed for ADLs (toothbrush, shaver, utensils, etc.). Based on feedback from users on space utilization, aesthetics, and time needed to access the supplies from the kiosk, a new workstation was developed to provide faster, more efficient task performance (see Figure 1).

To date, 20 high-level quadriplegics (neurological levels C3, C4, C5) with little no use of their arms or hands have participated in the evaluation of the third generation workstation. Each participant was first given a pre-test questionnaire, then used the system to perform the following pre-programmed tasks through voice commands:

- prepare meals (microwave, refrigerator)
- feed with utensils (using spoon and fork)
- brush teeth with electric brush and rinse

Figure 1. DeVAR (Desktop Vocational Assistant Robot)

- wash and dry the face
- shave the face with electric shaver
- get a drink with a straw
- bring mouthstick to user for typing
- operate environmental control unit (to use phone, lamp, radio).

A second questionnaire was given at the end of the user trials. Task performance was measured in terms of completion time, level of completion (reliability, thoroughness, outcome, etc.), and user satisfaction. Results of these posttests affirm the robotic workstation's quality of performance. The participants responded favorably to the system's sturdiness, safety, ease of use, obedience, value, and reliability. When asked: "Given what you know about a robotic aid, would you want one in your home?", 15 participants answered "maybe" and 3 answered "no" on the pretest. On the posttest, 17 answered "yes" and 3 answered "maybe"; no one said they would not want one at home.

STATUS The voice recognition capability, task performance efficiency, aesthetics, and task repertoire of the third-generation system continue to be improved based on user feedback obtained through clinical evaluation. An educational video and a tutorial on the DeVAR system have been made and are used in training prospective users. A fourth-generation workstation, emphasizing the combination of vocational and daily living activities, has been designed and will be taken into community vocational and home settings within the year.

Continued evaluation of the DeVAR system by disabled users and by medical and rehabilitation engineering professionals is critical in creating a robust, reliable vocational robotic workstation for the severely physically disabled.

PUBLICATIONS

Hall K, Glass K, Hammel J, Leifer L, Perkash I. Evaluation of a table top robotic aid for quadriplegics. *Proc 10th Ann Conf Rehabilitation Technology (RESNA)*, San Jose, CA, 1987.

Lees D, Crigler B, Van der Loos M, Leifer, L. Design of a second generation desk-top robotic aid. *Proc 10th Ann Conf Rehabilitation Technology (RESNA)*, San Jose, CA, 1987.

SUPPORT

VA RR&D Merit Review (1985-present)
VA Spinal Cord Injury Center
RR&D Core Resources

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Vocational Assessment of Severely Physically Disabled Individuals for Use of Robotics Technology

PROBLEM Few people with severe physical disabilities are able to find productive employment. One of the main reasons is that these people need attendants to care for them and to assist them in performing physically demanding tasks. A desktop vocational robotic aid has been designed that can take the place of a human attendant in performing many of these tasks, allowing the disabled individual to work more independently. The purpose of this study is to identify the tasks that such a robotic aid must be able to perform by evaluating the needs of disabled individuals who do hold successful jobs.

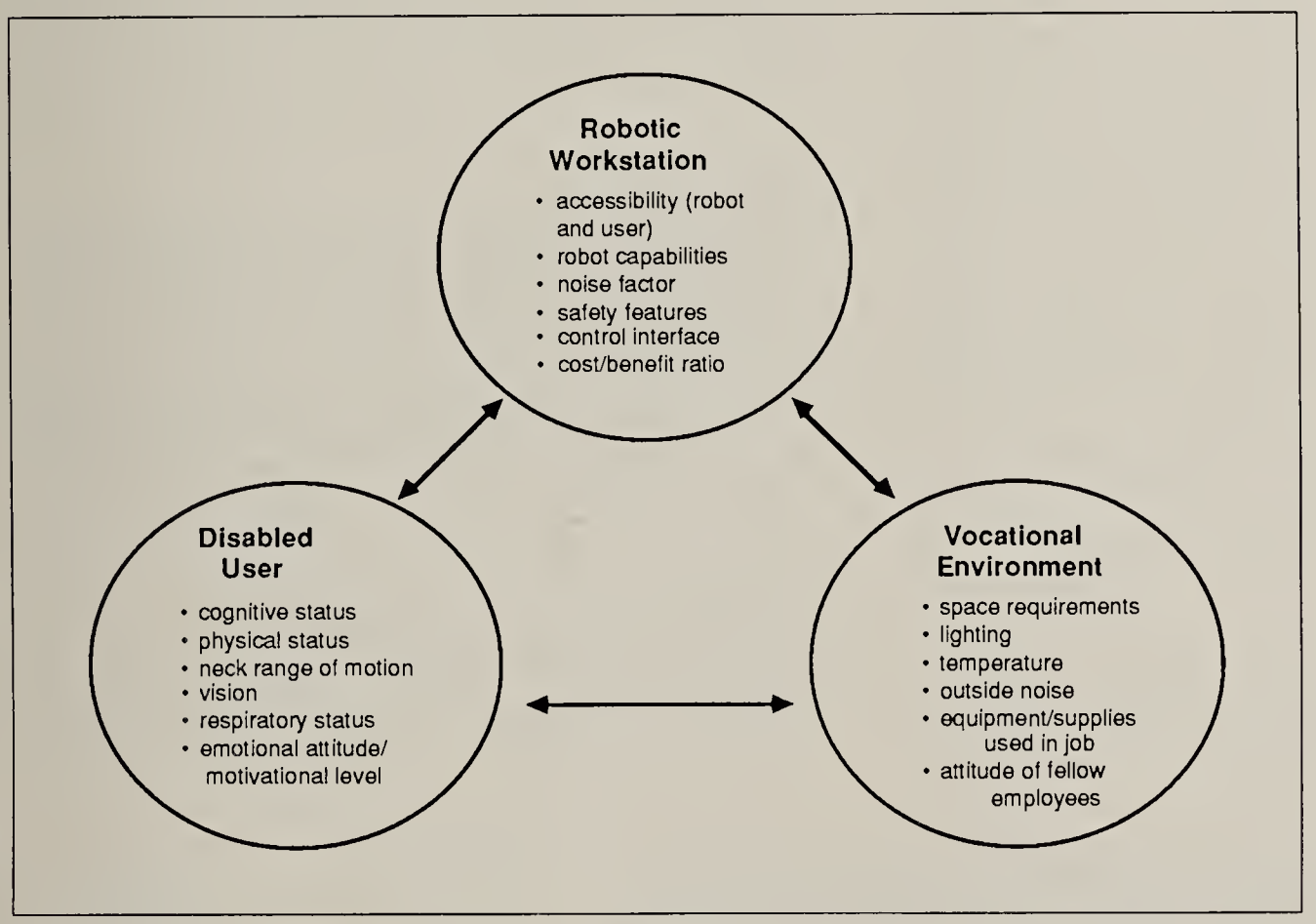

Figure 1. Human-machine interface considerations in a vocational environment.

SIGNIFICANCE Technology that can return severely disabled individuals to productive employment can have tremendous impact in many areas, including: decreased attendant and health care costs; increased revenue benefits to the disabled worker, the employer and the community; and the psychological benefit of giving the disabled person control and independence in his or her daily job performance. Robotics technology can offer this vocational opportunity to thousands of severely physically disabled individuals, including individuals with spinal cord injury, arthritis, cerebral palsy, and many other musculature and neurological disorders.

BACKGROUND The impetus for this work is based on the evaluation of a previous desktop robotic aid at the VA Spinal Cord Injury Center (see Report 40). That system primarily focused on performance of activities of daily living (ADLs), such as feeding, grooming, etc, and has been clinically evaluated by 20 high-level quadriplegics. Based on feedback from disabled users and the interest expressed from prospective vocational employers, DeVAR (Desktop Vocational Assistant Robot) has been developed.

HYPOTHESIS We believe that the vocational needs of disabled individuals can be best identified by on-site evaluations of workplaces where disabled individuals are currently employed. The results of these evaluations will serve to guide the design of the fourth-generation vocational robotic aid.

APPROACH On-site visits to three worksites were conducted. The three clients assessed were all C3 quadriplegics, two of whom were respirator dependent. All three were at least one year post-injury. All three were working as computer programmers, and had been established at their jobs for at least 6 months. One worked

for Stanford University, one for a major corporate business, and one at Disabled Programmers Incorporated, a private firm specializing in educating the severely disabled in computer technology.

The evaluation consisted of a preliminary on-site visit by a multidisciplinary team including an occupational therapist, two rehabilitation engineers, and a social worker. The following six factors were assessed during these visits:

(1) upper extremity status (motor and sensory control, head and neck control, spasticity)
(2) posture/seating status
(3) respiratory status (respiratory capacity, voice control and volume needed to operate the robot)
(4) cognitive status (attention span, ability to follow directions, education level)
(5) medical condition (pressure sores, bowel and bladder function, postural hypotension)
(6) ADL status (feeding, grooming and hygiene, transferring, wheelchair mobility, etc.).

A detailed breakdown of each task was performed by the therapist. Vocational tasks for which clients were dependent on others include: operating equipment (computer, printer); retrieving a mouthstick for typing; retrieving, setting up and paging through books and manuals; handling and responding to mail; and operating a phone. In addition to vocational tasks, each client needed to perform daily activities such as getting a drink and eating lunch. Each of these tasks can be performed efficiently by a desktop robotic aid, thus eliminating the need for a full-time attendant and giving the disabled client full control and independence in his/her environment (see Figure 1).

In performance of ADLs and vocational activities, all of the clients were maximally dependent on their attendants for continual assistance. The attendants were required to stay with the client for the full day (8 to 10 hours), actually doing active work for approximately 2-3 hours out of that time. Each client expressed problems with finding and retaining reliable attendants: one client had six attendants within one year. The robot could potentially offer the advantage of a reliable, nonemotional vocational aid and could be used to perform rote, repetitive tasks consistently.

In addition to task and attendant role analysis, the worksite was assessed for wheelchair and robot accessibility, fellow employee attitudes towards the disabled worker, and employer response to the use of technology to retain disabled workers. Both employers and disabled workers were very receptive to the addition of a vocational workstation.

Based on these evaluations, a fourth generation vocational robotic workstation has been developed which can allow the disabled worker to be independent for 4 to 10 hour periods. The robot is not intended to fully replace an attendant—one would still be needed for transferring and bowel and bladder care. Rather, the robot could make the disabled person maximally independent in all vocational and simple daily living tasks for extended and continuous periods of time.

STATUS Three extensive on-site evaluations have been conducted and written, including detailed task analysis, worksite pictures, and drawings of possible robotic workstation configurations. The fourth generation DeVAR system has been developed and will be taken into community vocational settings, including each of the three clients' worksites, within the coming year. Comprehensive ongoing evaluations of the robot's performance and upgrades to the system will continue to take place in the future.

PUBLICATIONS

Hall K, Glass K, Hammel J, Leifer L, Perkash I. Evaluation of a table top robotic aid for quadriplegics. *Proc 10th Ann Conf Rehabilitation Technology (RESNA)*, San Jose, CA, 1987.

Lees D, Crigler B, Van der Loos M, Leifer L. Design of a second generation desk-top robotic aid. *Proc 10th Ann Conf Rehabilitation Technology (RESNA)*, San Jose, CA, 1987.

SUPPORT

VA RR&D Merit Review (1985-present)
VA Spinal Cord Injury Center
RR&D Core Resources

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Daily Living Evaluation of High-Level Quadriplegics for Application of a Mobile Robotic Assistant

PROBLEM Individuals with severe physical disabilities, such as high-level quadriplegics, are dependent on a full-time attendant to meet the majority of their daily living, vocational, and recreational needs. These needs must be assessed in order to identify the role of high technology, such as robotics, as a means to address them.

SIGNIFICANCE The problem of locating and retaining a well-trained, reliable attendant is a continual concern for individuals with severe physical disabilities. This problem not only affects their health and daily care, but also their ability to maintain successful employment in the community. A mobile robotic aid can address this problem by giving the severely physically disabled maximal independence and control in home and vocational settings for extended and continuous periods of time.

BACKGROUND This ADL (activities of daily living) and vocational study is part of an ongoing research project to evaluate the use of robotics technology for the physically disabled. A desktop vocational assistant robot, DeVAR, that performs daily living and vocational activities has been clinically evaluated by 20 high-level quadriplegics from the Palo Alto VA Spinal Cord Injury (SCI) Center. This system will be placed in community settings within the year (see Report 40). A mobile vocational assistant robot, MoVAR, has been developed concurrently at Stanford University. This system offers the added capabilities of mobility, vision, and natural language. A need to extensively analyze the tasks to be performed by these systems has arisen from ongoing clinical evaluations and feedback from disabled users.

HYPOTHESIS It is hypothesized that by assessing whether, and for what time period, a disabled individual needs attendant assistance, the role of a mobile robotic assistant in performing these activities can be identified.

APPROACH We have gathered data on the ADL status of 30 high-level quadriplegics (neurological levels C3 through C6) who were rehabilitated at the SCI Center. Each patient was assessed by his or her occupational therapist at the time of admission post injury, at the release from the hospital, and at follow-up visits to the hospital, typically every six months. The assessment consisted of a checklist for evaluating the patient's level of independence in 90 tasks in the following ten categories: bed mobility, skin inspection, dressing, hygiene, bladder management, bowel management, transfer, wheelchair mobility, feeding, and communication skills.

Levels of independence were rated on a scale of 0 to 7 (completely dependent to completely independent) which was simplified to 3 functional levels:

- Dependent: Complete to high dependency with attendant needed for 50 to 100% of task completion
- Semi-dependent: The patient required set-up and/or stand-by attendant care, but little actual

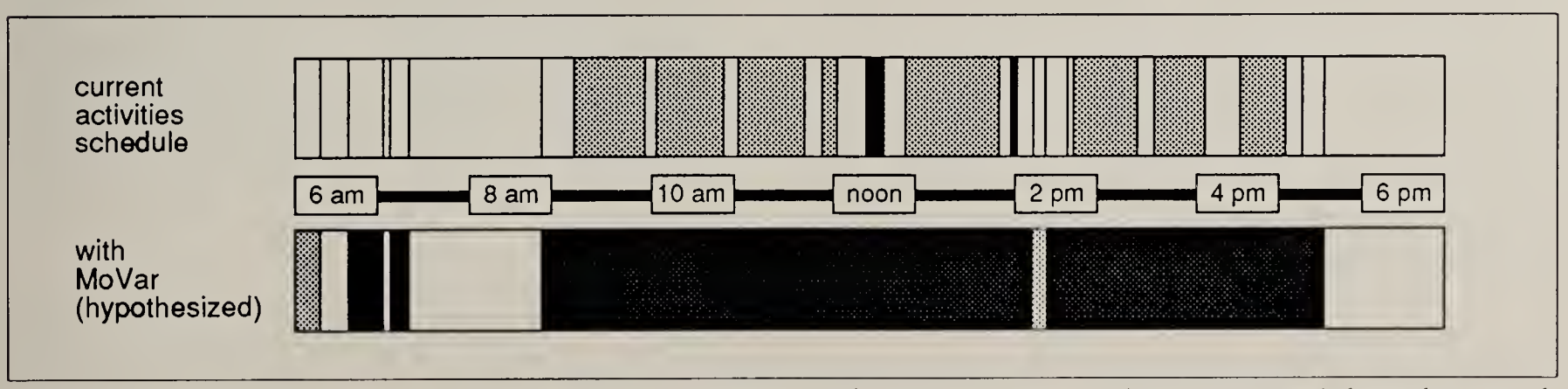


Figure 1. Influence of a mobile robot assistant in the workplace. Black denotes independence, grey semi-dependence, and white dependence.

intervention.

- Independent: The patient does not need attendant care for the specific task, but special equipment might be required.

Figure 1 shows the levels of independence in accomplishing these daily tasks during a typical day of a C3 quadriplegic who works as a full-time computer programmer. Black denotes independence, grey semi-dependence, and white dependence. The top of this figure shows that this individual is currently highly dependent on his attendant, except for periods of semi-dependence during work, when he needs his attendant to bring manuals, retrieve a mouthstick, dispatch material to co-workers, etc. The lower part of the figure shows the anticipated effect of providing a mobile robotic assistant. For this individual, the MoVAR robot can provide a major amount of independence during the work day. In this case, the remaining period of semi-dependence, which involves preparing food for lunch, could be managed with the assistance of a co-worker.

We believe this case is representative of a wide range of vocational scenarios in which severely physically disabled individuals could be employed with the assistance of a mobile robot. Furthermore, the manipulation capabilities of the robot can provide comparable levels of independence for disabled persons who remain at home and need to perform ADL, household and recreational tasks. This will have a significant impact on decreasing attendant costs, in addition to giving independence and control to the disabled robotic user.

STATUS ADL data on 30 high-level quadriplegics, with additional vocational data gathered from on-site visits to three quadriplegics' worksites, has been analyzed. Hypotheses on the role of the MoVAR system as a means to substantially increase the disabled user's level of independence in both the vocational and home settings have been made. Based on positive results from this analysis, a second generation MoVAR system is under development. Further clinical and on-site community evaluations studying the application of robotic technology for individuals with severe physical disabilities will continue to take place in order to upgrade the MoVAR system and provide an efficient robotic workstation.

PUBLICATIONS

Hall K, Glass K, Hammel J, Leifer L, Perkash I. Evaluation of a table top robotic aid for quadriplegics. *Proc 10th Ann Conf Rehabilitation Technology (RESNA)*, San Jose, CA, 1987.

Van der Loos HFM, Michalowski SJ, Leifer LJ. Design of an omnidirectional mobile robot as a manipulation aid for the severely disabled. *Proc 9th Ann Conf Rehabilitation Engineering (RESNA), Minneapolis, MN, 1986.*

Michalowski SJ. Navigational algorithms for a mobile robotic aid for the severely disabled. *Proc 10th Ann Conf Rehabilitation Technology (RESNA)*, San Jose, CA, 1987.

SUPPORT

VA RR&D Merit Review (1981-present)
RR&D Core Resources

Machiel Van der Loos, EngrD
Stefan J. Michalowski, PhD
Larry J. Leifer, PhD

Development of an Omnidirectional Mobile Vocational Assistant Robot for the Severely Disabled

PROBLEM Over the past two years we have developed a laboratory prototype of the mobile vocational assistant robot (MoVAR). While satisfactory as a proof-of-concept system, it must now be re-engineered for robust operation in clinical, home, and workplace environments away from expert engineering support. Sensor systems and fault tolerant programming methods are being applied to deal with these issues.

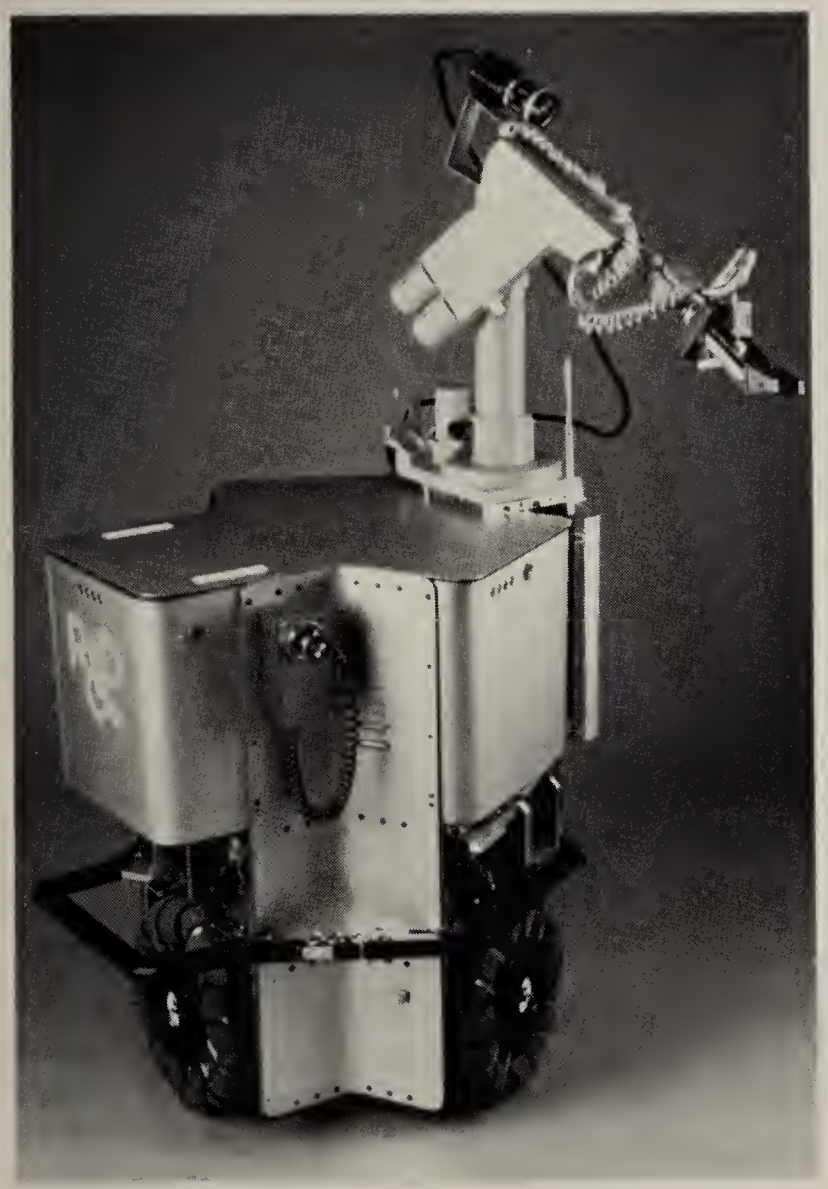


Figure 1. The latest prototype of MoVAR, the mobile vocational assistant robot for the severely disabled.

SIGNIFICANCE The user of any assistive device expects that technology will be robust and responsive to personal needs. Severely disabled individuals require support systems that are easy, safe, and reliable to operate and are tailored to their capabilities. If these performance goals are not met, even badly needed devices will not be acceptable. This project's current "technology hardening" phase has been designed to bring robot assistants one step closer to being commercially viable products.

BACKGROUND For robot mobility we have designed a unique omni-directional three-wheeled vehicle the size of an electric wheelchair. Emulating the ability of ambulatory persons, it is able to turn in any direction while moving forward or backward, left or right. The ability to shift sideways makes maneuvering in close quarters especially natural. This capability was demonstrated in the laboratory prototype of MoVAR. A small PUMA-260 robot arm is mounted on the waist-high mobility base. The manipulator is outfitted with a two-fingered gripper. The system is capable of retrieving objects from across the room or from another part of the house and bringing them to the user.

HYPOTHESIS Current development work is based on the hypothesis that safety and ease-of-use depend in large measure on the properties of our robot's sensory systems. Combined with omni-directional mobility, these systems allow the robot to adapt to the changing human environment.

APPROACH The basic mechanical and software features of the first prototype have not changed appreciably over the past two years. The next section enumerates the major subsystems we have developed to enhance the MoVAR's mobility and manipulation capabilities. Now, we are implementing these improvements using state-of-the-art components, advanced computer hardware, and integrated sensor systems. On completion at the end of this year, the entire system will be delivered to the Spinal Cord Injury Service's clinical robotics team for evaluation.

STATUS The laboratory system (see list of publications for detailed reports) was first assembled two years ago. It

has evolved since then to include:

- instrumented bumper system and software to respond to collision situations,
- laser scanner system, with wall-mounted reflectors, for position calibration,
- optical proximity sensors in the gripper, and software for automatic grasping,
- six-axis force sensor to measure gripper contact forces with the environment,
- TV-camera mounted on the arm, and radio link to console,
- software to use the camera to guide the user in following trajectories, and
- battery charge monitoring to warn the user of low battery condition.

The MoVAR is also benefiting from the availability of more efficient power supply components. It uses 75% less power than the first system, given high-efficiency power supplies, better power amplifiers, and new motor controllers for the three wheels and six arm joints. These enhancements, combined with a more capable computer and stronger motors, give this second-generation system a significant increase in autonomy and performance.

The real-time control program in the mobile base computer has been revised extensively to take advantage of these sensory enhancements and to increase the overall manipulation performance of the robot. Several quadriplegic users have helped us test the potential usefulness of this laboratory system.

PUBLICATIONS

Van der Loos HFM, Michalowski SJ, Leifer LJ. Design of an omnidirectional mobile robot as a manipulating device for the severely disabled. *Proc 9th Ann Conf Rehabilitation Engineering (RESNA)*, Minneapolis, MN, 1986.

Park H, Leifer LJ. Integrated sensory perception for a rehabilitative robotic aid. *Proc 9th Ann Conf Rehabilitation Engineering (RESNA)*, Minneapolis, MN, 1986.

Jameson JW, Leifer LJ. Quasi-static analysis: a method for predicting grasp stability. *Proc IEEE Internat Conf Robotics and Automation*, 1986.

Lee HS, Leifer LJ. Automated robotic grasping by use of optical proximity sensors. *Proc 10th Ann Conf Rehabilitation Technology (RESNA)*, San Jose, CA, 1987.

Park H, Leifer LJ. Object localization using multi-resolution sensing. *Proc 10th Ann Conf Rehabilitation Technology (RESNA)*, San Jose, CA, 1987.

SUPPORT

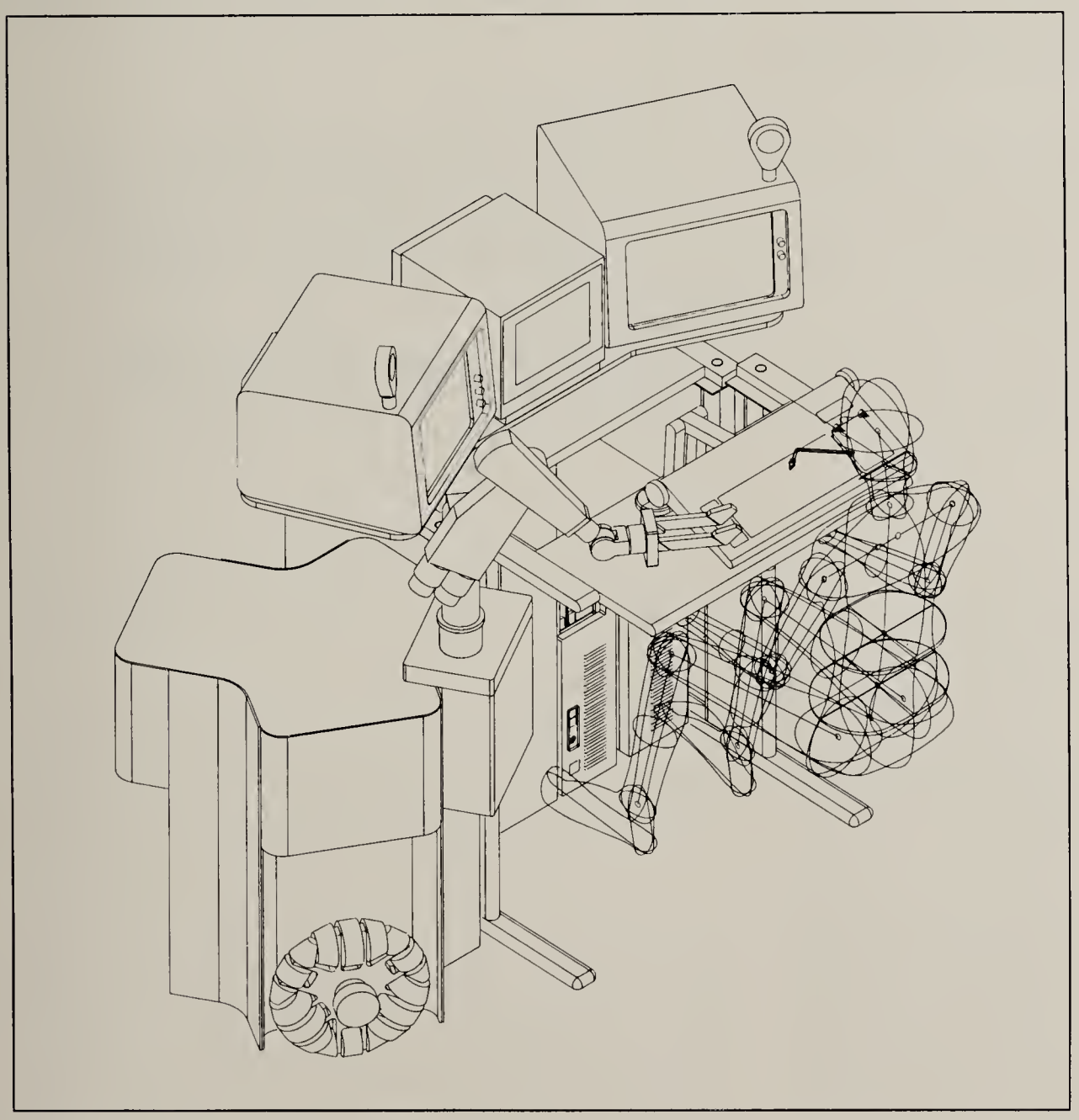
VA RR&D Merit Review (1981-present)
RR&D Core Resources

Douglas Schwandt, MS
Jeffrey Aldrich, DesInd
Machiel Van der Loos, EngrD

Design and Development of an Interactive Workstation for a Robotic Manipulation Aid

PROBLEM To become an effective part of the disabled user's environment, the mobile vocational assistant robot (MoVAR) Robotic Aid must satisfy both the technical requirements of robot supervision and control, and the human factors requirements of the user. The interactive workstation fulfills these potentially conflicting needs by integrating the input and output devices necessary to monitor and control the Robotic Aid into an aesthetically pleasing and ergonomically correct package. Previous experience with interactive control environments has demonstrated the need for modularity and open-ended design. These factors can enhance the user's perception of utility and "friendliness" and at the same time ensure that the device will continue to be useful as new technology becomes available.

SIGNIFICANCE The workstation is used by physically disabled persons with a wide range of disabilities requiring a variety of control interfaces. It provides the means for interactive supervision and control of the mobile robotic aid, communicating the user's commands to the mobile system and receiving continuously updated information from that system. To lessen the control burden on the user, greatly increased sensory capabilities have been provided for the second-generation Robotic Aid in the form of a touch-sensitive bumper system and a low-power laser scanner for the mobile base, and photoelectric proximity sensors and a force-sensing wrist for the robotic hand. The workstation is usable by both disabled and able-bodied persons, meets the needs of the technical development and clinical evaluation teams, and allows for multi-user interaction and easy group demonstration.



BACKGROUND The second-generation laboratory system uses an LSI-11 computer in the mobile base and an IBM PC-AT

Figure 1. Alternative component layouts and human factors for the interactive workstation were studied using computer-aided design technology. The plot includes a human figure which can be scaled and positioned in the drawing space to represent a range of possible users.

computer housed in the workstation. The system also includes a speech synthesis unit, a voice recognition unit, an ultrasonic head control interface (UHCI) for two-axis control of the mobile base and graphics screen cursor, a keyboard, and a video camera mounted on the robot to provide real-time visual feedback to the user. The LSI-11 computer communicates with the PC-AT central processing unit in the workstation through a radio link. Visual information is provided to the user on three screens: an alphanumeric display, a high-resolution graphics display, and a closed-circuit television monitor.

HYPOTHESIS It is proposed that an effective user interface to the Robotic Aid will result from meeting the following design criteria:

(1) The user is given a free choice between equivalent and equally accessible command modes: spoken commands through the voice recognition unit, typed commands through the keyboard, and "pointing" commands with UHCI in a manner analogous to using a joystick.

(2) A clear line of sight is maintained between the user and the mobile unit to facilitate monitoring of robot behavior and status.

(3) Information required for real-time supervision and control of the Robotic Aid is constantly available in the form of video images and graphic display of environmental data, while reference and diagnostic information are displayed only on demand.

(4) Flexibility in configuring these graphic displays and the physical layout of the workstation enables effective use of the robotic system in training, evaluation, and demonstration.

APPROACH Workstation design began with a literature and product search in the area of interactive human-machine systems, with topics ranging from telemanipulation and space station design to shared attention environments and display devices. Product searches included investigation of flat panel display technology, touch screens, laptop computers and keyboards with infrared links. Device evaluation centered on power specifications, compatibility with existing equipment, human factors, size, weight, and cost.

The design of this workstation has been likened to the design of a vehicle dashboard. Both require that special attention be given to the operator's unobstructed view of the environment while maintaining displayed status and control information in clear view, to the user's reach envelope for controls (by hand or mouthstick), and to knee and leg—or wheelchair—clearance for comfort and accessibility. In acquiring anthropometric data, an effort was made to address the physical needs of the greatest number of users while considering their visual and functional capabilities.

STATUS The latest prototype was designed as an integrated unit to include storage space, work surface, and input/output devices in a modular tabletop overlay which can be mounted on a table structure of the user's choice. Work currently proceeds on a development version intended for laboratory testing and off-site evaluation. This version will present a more integrated approach to component distribution in the workstation, providing greater flexibility in locating the device in non-laboratory settings. Additionally, greater adjustability of the individual input/output devices and of the workstation as a whole will improve the fit between user and task. Significantly, nearly all adjustments will be able to be performed by the user, independent of the assistance of an able-bodied person.

PUBLICATIONS

Holloway K, Leifer L, Van der Loos HFM. Factors in the design and development of an interactive human-robot workstation. *Proc 8th Ann Conf Rehabilitation Engineering (RESNA)*, Memphis, TN, 1985.

SUPPORT

Center for Design Research, Stanford University
VA RR&D Merit Review (1981-present)
RR&D Core Resources

Larry Leifer, PhD
Stefan J. Michalowski, PhD
Laurence Edwards, MS

The Next-Generation User Interface for an Assistive Robot

PROBLEM Robots can provide useful daily-living and vocational assistance for veterans with severe physical disabilities. An assistive robot must be under the control of the user at all times. A variety of physical interface devices and modes of operation are being explored to optimize the human/robot interaction. To accommodate changes in hardware and to allow experimentation with various concepts in interface design, a flexible and modular software architecture must be designed. Although this architecture is important from the developer's point of view, for the disabled user the crucial aspect of the system is the actual interaction. To this end one must make effective use of color cues in the displays, voice input and output, and other ways to communicate information to the user. Since the system is being developed for a microcomputer environment, considerations of efficiency, size, and cost also play a major role.

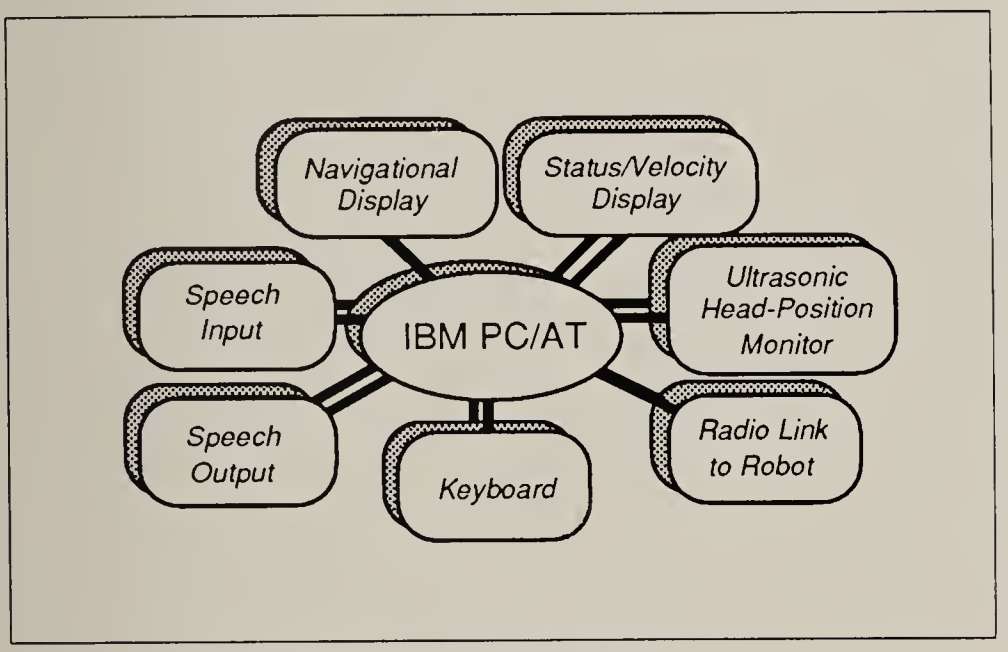


Figure 1. System architecture of the user interface for the Mobile Robotic Aid.

SIGNIFICANCE In some ways, the user interface constitutes the most important component of an assistive robot system. Users typically know exactly what they want a robot to do during a given task. The robot's ability to grasp and manipulate objects is also adequate in most cases. The difficulty lies in conveying the user's knowledge and wishes to the robot, *i.e.*, in creating an efficient interface system.

BACKGROUND The original Robotic Aid had a text-only diagnostic terminal, a rudimentary speech synthesis system, and a small status display. Input was limited to a 58-word spoken command vocabulary. Users and researchers agreed that all aspects of the system needed to be enhanced. The current system employs an IBM PC/AT microcomputer with a 80286 central processing unit. The workstation incorporates state-of-the-art speech input/output (I/O) and high-resolution color displays along with an ultrasonic head-position sensor. A black-and-white television monitor allows the user to view a close-up image of the manipulation scene, transmitted from a small camera mounted on the robotic arm.

HYPOTHESIS We hypothesize that the use of high-quality real-time color displays along with speech I/O will allow extensive information exchange about the state of the Robotic Aid to be presented to the user in a comprehensive way. The system will be easier to use, easier to learn, safer, and more efficient.

APPROACH We use the IBM PC/AT microcomputer with the Professional Graphics Controller and Enhanced Graphics Adaptor. The software development environment is Borland TurboPascal version 4.0. A Kurzweil KVS and Dectalk provide speech input and output capability.

STATUS Two graphic display screens are now implemented. The first provides a high-resolution color map of the surrounding area, including the current location of the mobile robot. this display is particularly useful when piloting the vehicle through regions that are not directly visible to the user. It also provides a way to define trajectories (by using the ultrasonic head-position detector)

that can be executed by the robot. The display also includes a field showing the last recognized command and any messages from the robot. The second screen provides a graphical representation of the motion state of the robot (arm or vehicle). Users no longer have to remember all of the commands that they have already given, thus allowing then to steer the robot without the need to stop its motion at frequent intervals. The second display also indicates which of the robot's sensory subsystems and autonomous motion routines are active.

SUPPORT
Center for Design Research, Stanford University
VA RR&D Merit Review (1981-present)
RR&D Core Resources

Stefan J. Michalowski, PhD

Navigational Algorithms for a Mobile Robotic Aid

PROBLEM Physically disabled veterans need to control their physical environment to achieve personal independence. Desktop-mounted robots have been shown to provide useful daily-living and vocational support. Mobile robots further extend the range of manipulation to include an entire home or workplace. To perform correctly, a mobile robot's onboard computer must keep track of its position and orientation with respect to the user and surrounding objects.

SIGNIFICANCE The ability of a mobile robot to determine its location is crucial for such important tasks as moving in directions specified by the user and avoiding collisions with known obstacles.

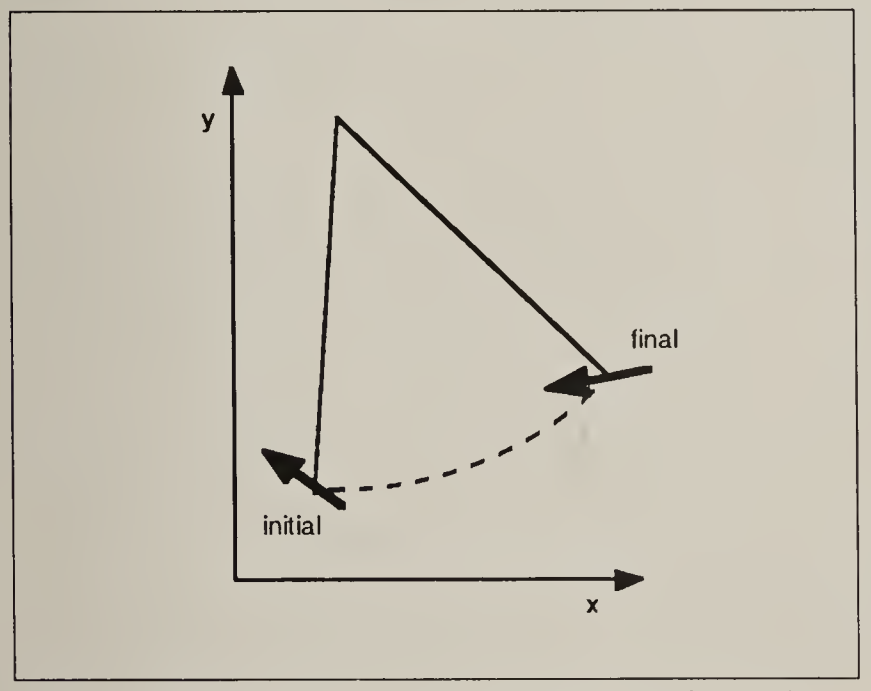


Figure 1. Motion of the robot along the arc of a circle. The thick arrows indicate the initial and final orientations of the robot. The coordinate axes are fixed with respect to the laboratory.

BACKGROUND The Stanford/VA Mobile Vocational Robot (MoVAR) consists of a robotic arm mounted on a three-wheeled omnidirectional base. A disabled user can command and control the motion of the robot by giving explicit direction commands such as *"north" or "left,"* or by activating previously defined trajectories.

The motions of the three wheels, which are arranged along the sides of an equilateral triangle, are supervised by an LSI-11/73 computer and monitored by optical shaft encoders. Free-wheeling rollers are distributed along the circumference of each wheel, allowing the wheel to move parallel to its axis of rotation. The total angular motion of each wheel is computed at a rate of 30 Hz (once every 33 milliseconds). The problem lies in deriving the angular motions so as to minimize the cumulative errors in the robot's position and orientation.

HYPOTHESIS During each 33 millisecond interval, the actual motions of the wheels are controlled by individual servo-controllers. The detailed history of the motions is not accessible to the supervisory computer. Therefore, the assumption is made that the wheels move with constant velocity during each 33 millisecond interval. This allows the navigational problem to be solved analytically.

APPROACH Small motion increments of the vehicle can be expressed as a pure translation, combined with a pure rotation about the center vertical axis. The corresponding angular motions of the wheels are given by

$$d_1 = A \cdot (D_x + \sqrt{3} D_y) + B \cdot D_r$$

$$d_2 = A \cdot (D_x - \sqrt{3} D_y) + B \cdot D_r$$

$$d_3 = -A \cdot D_x + B \cdot D_r$$

where D_x and D_y are orthogonal components of the translation vector (expressed in a coordinate system that is fixed with respect to the robot), D_r is the desired rotation, and A and B are constants that depend on the radius of the wheels, the distance of the wheels from the center of the robot, and the gear- and chain-drive ratios. The actual motion of the vehicle is an arc of a circle (see Figure 1). Thus, an arbitrary trajectory can be realized, if it is broken up into small arc segments, each one traversed during 33 milliseconds with the appropriate constant wheel velocities.

STATUS The current version of the mobile robot uses the constant-velocity approximation to control the direction of motion and to update the position and orientation. Measurements of positional accuracy reveal that the navigational errors are on the order of 2%, and that the most significant source of error is the mechanical misalignment between the rollers and plane of the wheel. Accordingly, the robot prototype now being assembled will be equipped with a new, improved set of wheels.

PUBLICATIONS

Michalowski S. Navigational algorithms for a mobile robotic aid for the severely disabled. *Proc 10th Ann Conf Rehabilitation Technology (RESNA)*, San Jose, CA, 793-795, 1987.

SUPPORT

VA RR&D Merit Review (1981-present)

Stefan J. Michalowski, PhD
Colleen Crangle, PhD[1]
Lin Liang, MS[1]

An Instructable Robotic Aid for the Severely Disabled

PROBLEM Physically disabled veterans need to establish direct control over their environment to achieve personal, vocational, and financial independence. Speech-controlled devices, such as robots and environmental controllers, offer important advantages for the rehabilitation of veterans whose arm and hand functions are severely impaired. Unfortunately, current technology limits the usefulness of speech-controlled devices: (1) They require extensive user training. (2) Users have to memorize large and complex vocabularies. (3) Expert programmers must be employed to adapt the devices to the needs of individual users. (4) There are hazards associated with errors in speech recognition. There is a need to increase the rehabilitative value of speech-controlled devices.

SIGNIFICANCE A disabled person, like most able-bodied persons, is a computer *user*, not a *programmer*. If the full potential of the many devices now under development for the disabled is to be put at the disposal of the user, it is essential that a way be found to enable non-programmers to communicate with these devices. It is also essential that the user be allowed to train general-purpose robotic devices to perform new tasks of the user's choosing.

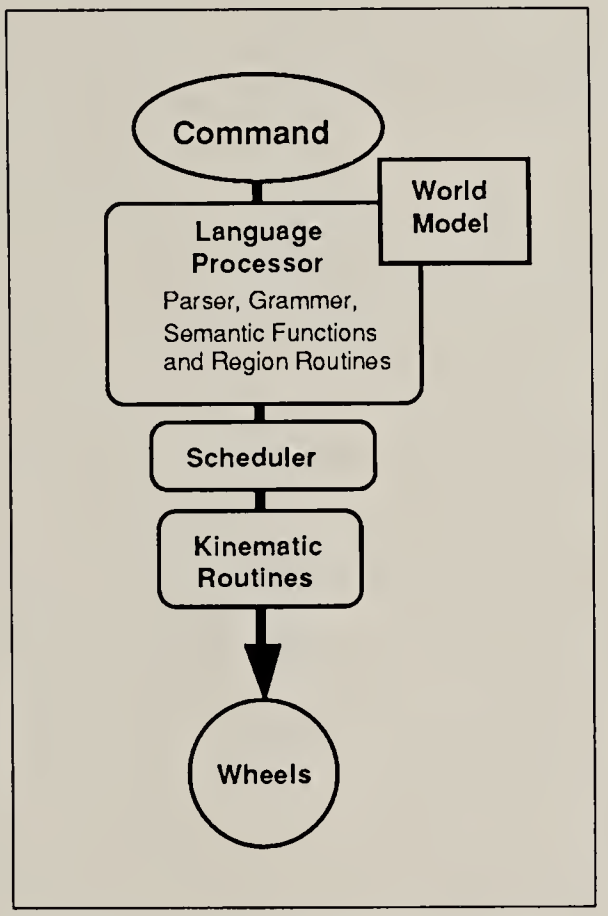


Figure 1. System architecture for the preliminary version of the Instructable Robotic Aid

BACKGROUND Since 1980, the RR&D Center has been developing voice-controlled robots for assisting the severely disabled. The latest prototype is a voice-activated, mobile manipulation system that can be used to perform a variety of household and vocational tasks. During the past two years, we have been exploring ways to facilitate access to our robots by disabled users.

HYPOTHESIS We hypothesize that physically disabled users can communicate with a robot using ordinary, colloquial English. Through the use of commands and questions, users will teach the robot to perform useful tasks of increasing complexity.

APPROACH We are using techniques of natural-language processing and machine learning to develop a new type of human/machine interface for the Stanford/VA Mobile Robotic Aid.

STATUS A pilot study has been completed. A preliminary version of a natural-language interface now exists for the motion base of the mobile robot. The goal has been to create the basic software tools for commanding the robot's motions in an enclosed room containing a few objects, whose locations are known to the robot. Although the system is restricted in many ways, the robot can now understand and execute correctly such commands as *"Go slowly towards the desk and stop if the bumper is hit."*

The system architecture is shown in Figure 1. The Language Processor analyzes the spoken command from the user, and produces an Interpreted Command which contains information about the following: (1) which of the robot's generic motion routines are to be invoked; (2) the temporal order of execution and the logical conditions under which the motion routines are to be activated and terminated; (3) the parameters of any spatial regions that may have been referred to in the command. The Scheduler invokes the motion routines in real time, based on the contents of the Interpreted Command.

1. Stanford University

PUBLICATIONS

Michalowski S, Crangle C, Liang L. Experimental study of a natural-language interface to an instructable robotic aid for the severely disabled. *Proc 10th Ann Conf Rehabilitation Technology (RESNA),* San Jose, CA, 773-775, 1987.

SUPPORT

VA RR&D Pilot Study (1988)
RR&D Core Resources

Colleen Crangle, PhD[1]
Lin Liang, MS[1]
Larry Leifer, PhD
Patrick Suppes, PhD[1]
Michael Barlow, MS[1]

Using English to Instruct a Robotic Aid: An Experiment in an Office-Like Environment

PROBLEM When people and robots interact, some common language has to be found to allow them to talk to each other. If general-purpose robotic devices such as the Robotic Aid (see Report 36) are to be of use to physically disabled people, it is crucial that we solve the problem of communication. Few people in the general population or in the disabled community have the training or aptitude to learn a robot programming language. If we rely on specially trained technical personnel to program the Robotic Aid, however, the result will be a robot that can perform only a fixed set of predefined tasks. Such a robot would not meet the varied and changing needs of individual users.

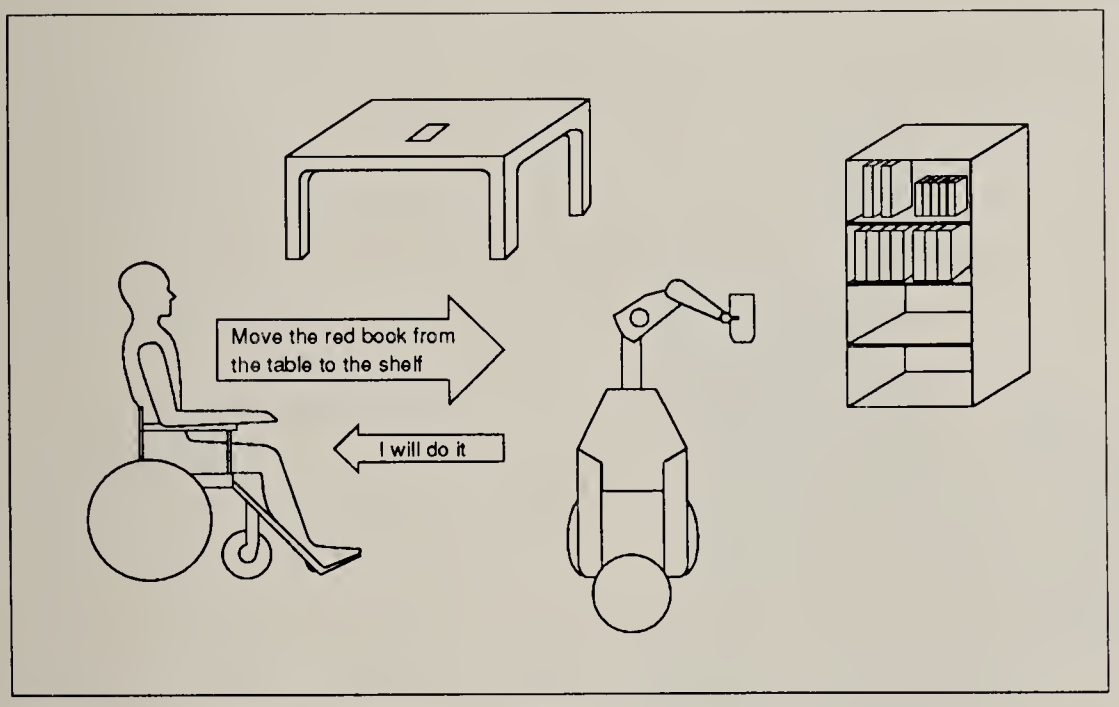


Figure 1. Communicating with the Robotic Aid in English.

Intermediate languages have been designed to help bridge the gap between human and robot but they have proved frustrating to the user. They have also proved inadequate for controlling a device like the Robotic Aid that has to operate in a complex and changing environment. What we need is a robot that can understand an ordinary, human language such as English.

SIGNIFICANCE The Robotic Aid has enormous potential to help physically disabled people gain independence and some control over their environment. It will fulfill its potential, however, only if two things come about: (1) users can speak to it using a natural language such as English, and (2) users can teach the robot in English, as one would teach a child, to perform new tasks. In this way each person will be able to adapt the device to his or her own abilities and needs. The result will be a robot that can provide a significant degree of independence, and intellectual satisfaction, to the physically disabled user.

BACKGROUND Work on natural-language instruction for the Robotic Aid grew out of a collaboration between the Stanford/VA Robotic Aid project and work on natural-language instruction at the Institute for Mathematical Studies in the Social Sciences at Stanford University. In an experiment conducted during 1986/87, a natural-language interface was built for the omnidirectional vehicle of the Robotic Aid (see Report 43). The result was that the robot would obey commands such as *"Go to the other side of the chair"* and *"Whenever you are within two feet of the stairs, stop."*

The crucial next steps in this program of work were (1) to apply the techniques developed in the first experiment to the robot arm and gripper, and (2) to show how natural-language instruction can be used to teach the robot a new task.

HYPOTHESIS We believe that a natural-language interface for the Robotic Aid will allow the physically disabled user to communicate naturally and effectively with the robot. We also believe that the robot can be taught, in English, to perform useful tasks. The Robotic Aid's potential in the home environment has already been demonstrated with tasks of personal hygiene and eating. Its application in the work environment, however, is just as promising. We believe an instructable Robotic Aid has the potential to open up new employment opportunities

1. Stanford University

for the physically disabled person. We are presently examining the robot's use in an office-like environment: a room containing a table, a bookcase, and books of various sizes and shapes. We want the user to be able to teach the robot to perform organizational tasks such as sorting the books, packing them into or out of the bookshelf, and rearranging the books on the shelves.

APPROACH The robot starts out with several basic actions that it can already perform—such as picking up a single book, putting a book down on the table, placing a book upright on a shelf, and pushing a book along the surface of the table. As with all complex robot actions, these will work in some circumstances and not in others. Our experiment shows how the user can teach the robot what to do in a new circumstance—what to do, for instance, when the robot has been told to put a book on the shelf and there is not enough room for it.

Because the robot has no vision system, we have provided it with a map of its environment showing the initial location and orientation of all objects. This store of information is called the robot's database. The robot gets information about objects referred to in English from this database (*e.g.,"the red book at the end of the shelf"*) and updates the database every time it moves a book from one location to another.

STATUS We have completed the following six steps required for the experiment:

(1) Transferred the natural-language software from the previously used computer system (a Micro Vax II) to the Symbolics 3650, a LISP machine that is better suited to artificial intelligence applications such as this one.
(2) Programmed the computer onboard the robot for the primitive robot actions.
(3) Programmed the robot's database.
(4) Designed and programmed an intermediate level of actions between the robot and the human—the basic actions.
(5) Written the grammatical rules and the rules of interpretation using the grammar development system D-PATR. These rules take the basic actions and use them to produce a coded command that the robot understands.
(6) Designed and programmed the Dialogue Manager, a piece of software that lets the robot tell the user what tasks it cannot yet perform and then remembers the user's instructions about that task for the next time.

ACKNOWLEDGEMENTS

We wish to acknowledge the support of the following facilities at Stanford University: Institute for Mathematical Studies in the Social Sciences, Center for the Study of Language and Information, and Center for Design Research. We also acknowledge Dr. Lauri Karttunen for developing the D-PATR system.

SUPPORT

VA RR&D Pilot Study (1988)
RR&D Core Resources

David L. Jaffe, MS

Ultrasonic Head-Controlled Wheelchair and Interface

PROBLEM High level quadriplegics have lost the use of their arms and legs. Anything they want to do for themselves, such as turning on a light, typing a letter, or operating a wheelchair, can only be accomplished using the muscles they can still control—those of the neck and head.

SIGNIFICANCE We have developed a device that allows a severely paralyzed person to use his or her head as a joystick for controlling electrical and mechanical equipment. The device employs ultrasonic distance ranging to determine the location of the head without making physical contact. It has proven to be natural to use and can be applied to a variety of tasks to give a disabled user more independence in controlling his or her mobility, communication, and recreation. In addition, it is inexpensive to manufacture, which we hope will lead to mass production and widespread use.

BACKGROUND While many control interfaces have been developed for use by severely disabled individuals, none are ideal. Some have sanitation problems (pneumatic puff/sip switches), while others may physically intrude upon the user (chin-operated joysticks) or may be socially objectionable (head wands).

Technologically advanced approaches have drawbacks of their own: eye control units unduly restrict the user's gaze, while voice-control provides inadequate responsiveness. These and other options are limited in their ability to convey the will of the user to operate the attached device in a socially acceptable and aesthetically pleasing manner.

Figure 1. Quadriplegic woman using Ultrasonic Head-Controlled Wheelchair.

HYPOTHESIS We have hypothesized that an array of ultrasonic distance-ranging sensors can monitor the head position of a severely disabled quadriplegic individual to obtain real-time proportional information for the control of mobility, communication, and robotic devices. As these sensors require no direct mechanical contact, a more socially acceptable and cosmetically pleasing interface has resulted.

APPROACH We have developed a new type of human-machine interface based on an ultrasonic distance ranging technique. Two Polaroid transducers are mounted on an electric wheelchair frame and aimed at the rider's head. The transducers emit inaudible high-frequency sound waves that propagate through the air and are reflected by the head. The resulting echoes are detected by the transducers.

The distance from each transducer to the head is calculated from the elapsed time between transmission of the sound and reception of the echo. The two distance measurements allow determination of the user's head position, which is then mapped into a two-dimensional control space.

To use the Ultrasonic Head-Controlled Interface, the user simply tilts his or her head forward or backward, left or right, just as he or she would in manipulating a joystick. The resulting control signals can be used to operate an electric wheelchair, a communication aid, a video game, or a robotic arm.

The main advantage of the UHCI is that it requires no mechanical contact between the transducers and the user's head. The user, therefore, does not feel "wired up" as he or she might with other interfaces that have components touching the head or in close proximity to the face. By being unobtrusive, the UHCI is also cosmetically pleasing and socially acceptable.

STATUS Two UHCI-controlled electric wheelchairs have been in operation since 1983. One is an Everest and Jennings model 3P with a reclining Recaro seat that belonged to a quadriplegic woman in France. The other is an Invacare Rolls IV with a Solo Products Power Pack that is being evaluated at the Spinal Cord Injury Center at this VA Medical Center.

User evaluation was performed with ten quadriplegic individuals. Most of them were able to navigate the modified wheelchair successfully after a brief training session and demonstration. They found the UHCI to be more intuitive to operate, easier to use, less demanding in terms of concentration, and less tiring than conventional chin-controlled wheelchair controls.

We have also developed a generalized interface using the UHCI that allows the user to control the operation of a mobile robotic arm. In operation, the user controls the robot's path by using head motions to draw a trajectory on a CRT screen.

A technical manual for the UHCI has also been compiled. It includes background material, electronic schematic, computer program listings, explanations, and illustrations that will enable other engineers to build UHCIs for their own applications. This manual is in the hands of seventy-five interested investigators around the world who are considering using the UHCI for research or commercialization.

Within the VA, funds have been approved by the RR&D Evaluation Unit, and a manufacturer has been selected to build four commercial prototype units for VA testing and evaluation. These units are scheduled for delivery in October, 1988. If the evaluation is favorable, the VA is expected to allow wheelchairs incorporating UHCIs to be prescribed for appropriate disabled veterans.

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SUPPORT

Paralyzed Veterans of America (1983)
VA RR&D Evaluation Unit (1987-present)
RR&D Core Resources

Janice McKinley, MA[1]
David L. Jaffe, MS
Howard Lauren, MA[1]

Minimal Information Sensor System: A Mobility Aid for the Visually Impaired

PROBLEM The most commonly used mobility aid for blind travellers, the long cane, only provides protection below the waist. Obstacles present in the environment above waist level, such as overhanging tree branches, are not detected prior to contact.

SIGNIFICANCE The development of an effective aid to detect potentially hazardous obstacles in the environment above the waist could increase the safety and confidence of blind travelers.

BACKGROUND The long cane has proven to be an effective and low-cost solution for handling one of the most dangerous aspects of travel for a blind person—the detection of drop-offs such as stairs and curbs. The cane also detects low obstacles and affords some protection against obstacles located below the waist. However, the entire upper portion of the body remains vulnerable to protruding obstacles above waist height (see Figure 1). Common examples are signs hanging to the side of a post, scaffolding, trucks sitting crosswise blocking a sidewalk, boards and pipes extending from a vehicle, and overhanging stairways. Of particular concern is the head area, the portion of the body most likely to be damaged seriously by such an encounter.

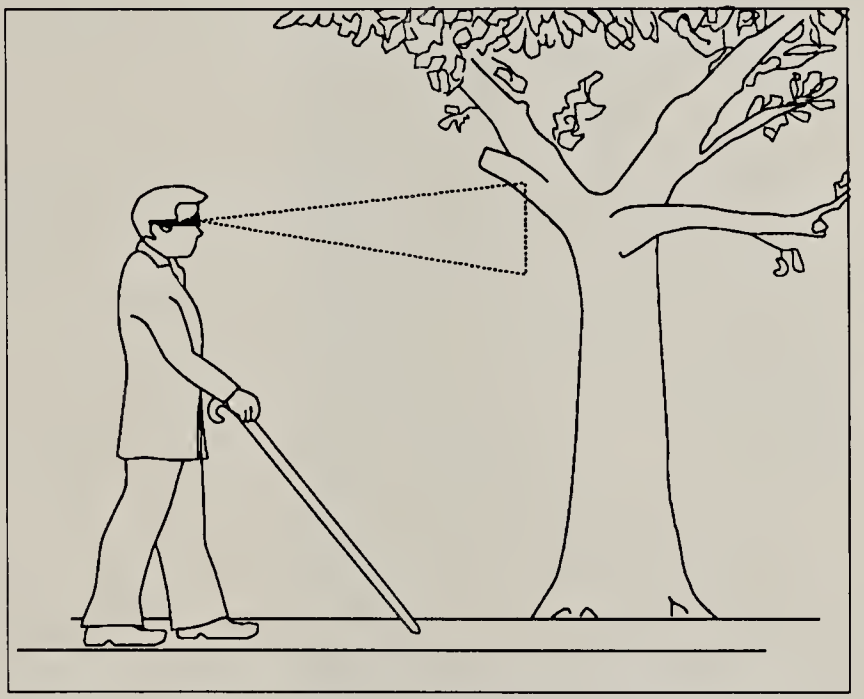

Figure 1. Head-high obstacles are not easily detected.

Electronic travel aids for the visually impaired, which supplement the use of the long cane, have been developed over the last twenty-five years. Many of these aids are capable of detecting obstacles above the waist when used in addition to the long cane. However, these aids have more extensive functions and are not designed primarily for head-high obstacle detection. Electronic travel aids are currently used by a small number of visually impaired travelers (1 to 2%). Generally, electronic aids are either cumbersome in size, cosmetically unattractive, expensive, or use a coded format that is difficult for the user to learn and to interpret while traveling.

HYPOTHESIS A simple electronic device that would emit a warning when a head-high obstacle is encountered at a relatively close distance (3 to 5 feet) would enhance the safety and confidence of blind travelers. Several criteria must be met for the aid to be both effective and accepted for use by the visually impaired traveler. The aid should be small in size, worn on the body rather than hand held, cosmetically acceptable, unobtrusive to others in the environment, without visible wires and power packs, easy to use, reliable, and low in cost (under $200).

APPROACH Preliminary studies have included simulation experiments using human subjects, trials with existing electronic travel aids, assessment of the needs of visually impaired travelers and a survey of existing aids to determine if any can be used as the hypothesized aid. This information has been used to determine the specifications of a simplified electronic travel aid to be used in the development of a prototype device. Devices that meet or partially meet the requirements specified will be tested by visually impaired subjects traveling routes in the community under the supervision of orientation and mobility instructors.

STATUS Simulation experiments have been completed which demonstrate the effectiveness of a simplified

1. Western Blind Rehabilitation Center

warning system for blindfolded travelers while using a long cane. A survey of orientation and mobility instructors in the field of blind rehabilitation indicates a need for the hypothesized device and further defines target characteristics. This preliminary work is being used to apply for funding that would allow testing of a prototype device to determine the effectiveness of this type of warning system. Pilot project funding is being sought for further research including fabrication and testing of a prototype head-high obstacle detector.

SUPPORT

Western Blind Rehabilitation Center Resources
RR&D Core Resources

Douglas Schwandt, MS
Larry Leifer, PhD
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James Anderson, Exp Mach
Anne Marie Glenn, MD[1]

The Handbike: an Arm-Powered Bicycle

PROBLEM Whether for exercise, therapy, recreation, sport, or self-powered transportation, bicycling is a popular activity providing many physical, psychological, and social benefits. Bicycling is potentially as natural and revitalizing an activity for the physically challenged as it is for the able-bodied. The major obstacle has simply been the design and availability of a suitable arm-powered bicycle.

SIGNIFICANCE An arm-powered bicycle will offer physically challenged individuals the dignity, the control, and the exhilarating freedom of balancing and riding a bicycle. Besides the direct individual benefits, an arm-powered bicycle will also enhance the integration and public awareness of the physically challenged.

BACKGROUND Arm-powered tricycles have been in use for at least 60 years. In addition, several companies market an attachment that converts a wheelchair into a tricycle.

The first arm-powered bicycle, called the Para-Bike, began as a VA sponsored student project in the Stanford University Mechanical Engineering Design Division during the 1979/80 school year. Development of several successive prototypes continued at the RR&D Center, culminating in a pre-production model, renamed the Handbike (see Figure 3).

The Handbike features drive, steering, and power input at the hand cranks. Adjustable side casters smoothly touch down at the desired lean, and also fasten down for four-wheel maneuverability indoors. An optional folding crank tower facilitates transfer to and from wheelchairs.

HYPOTHESIS The technology to develop arm-powered bicycles with features responding to special physical needs can be drawn from recent advances in arm-powered tricycle, human-powered vehicle and sport- wheelchair design. A suitable arm-powered bicycle design will improve the quality of life for the many physically challenged individuals who are eager to ride a bicycle.

APPROACH The approach has been to design, build, and test successive prototypes, incorporate improvements, evaluate alternative configurations, and document the preferred design for transfer to a manufacturer.

Figure 1. The Handbike features drive, steering, and power input at the hand cranks. It is seen here ready for evaluation.
Photo by Curt Campbell.

1. Spinal Cord Injury Center

STATUS A set of layout and detail drawings have been constructed using computer-aided-design facilities at the Stanford Center for Design Research (see Figure 2). A training manual has been written and six Handbikes have been built for the current evaluation phase (see Figure 1), to be carried out under the auspices of the VA Rehabilitation R&D Evaluation Unit and the Paralyzed Veterans of America. A company is now planning production of the Handbike to be available in Summer, 1988.

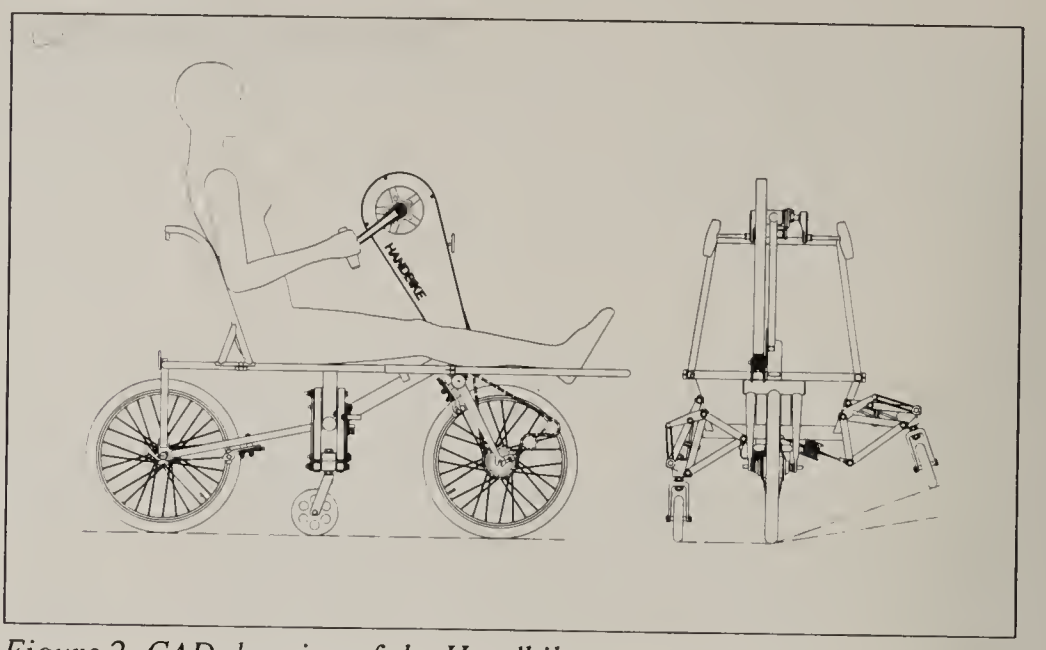

Figure 2. CAD drawing of the Handbike.

ACKNOWLEDGEMENTS

Design and construction contributions were made by: Gordon Abraham, Phil Barkan, Keith Bontrager, Gary Hale, Irv Housinger, Peter Johnson, Candy Mintz, Chris Schwandt, Fred Tatch, and Kate Hunter-Zaworski.

PUBLICATIONS

Schwandt DF. Design development of arm-powered bicycles for the disabled. *SAE*, paper 840023, 1984.

Schwandt DF. Para-Bike: an arm-powered bicycle. *Proc. 6th Ann. Conf. Rehabilitation Technology (RESNA)*, San Diego, CA, 3:378-380, 1983.

SUPPORT

Telephone Pioneers of America (1981)
British Columbia Program for the International Year of the Disabled Person (1981)
University of British Columbia Athletic Department
ME Design Division, Stanford University
Center for Design Research, Stanford University
VA RR&D Evaluation Unit (1986)
RR&D Core Resources

Figure 3. The Handbike, preproduction model.

Douglas Schwandt, MS
Larry Leifer, PhD
James Anderson, Exp Mach
Anne Marie Glenn, MD[1]

The Sunburst: a Tandem Bicycle for Both Able and Physically Disabled Riders

PROBLEM Individuals with physical disabilities resulting from paraplegia, low level and incomplete quadriplegia, amputation, muscular dystrophy, multiple sclerosis, stroke, cerebral palsy, blindness, etc., endeavor to live healthy and meaningful lives. They may benefit greatly in their physical, psychological, and social well-being from participation in the popular recreational activity of bicycling.

Figure 1. Handbike Tandem, first prototype.

SIGNIFICANCE A tandem bicycle for individuals with and without disability will literally provide a vehicle for integrated mobility and recreation. On such a tandem many who have been excluded from the revitalizing activity of bicycling will experience the freedom, exhilaration, and accomplishment of riding on two wheels.

BACKGROUND As a spin-off from the development of the Handbike, the first tandem prototype, called the Handbike Tandem, for disabled and able-bodied to ride together was completed in June, 1983 (see Figure 1). The Handbike Tandem is conceptually a merging of a Handbike and a standard bicycle. In the interest of independence and equality, it is designed to be ridden by one rider alone in either the front or rear position.

HYPOTHESIS The experience gained from the Handbike and Handbike Tandem leads directly to the design of the second prototype, called the Sunburst (see Figure 2). A commercially available version of the Sunburst is expected to provide the physically challenged with the many benefits of tandem bicycling.

APPROACH Although similar to the Handbike Tandem in rider configuration, the Sunburst (completed in June, 1984) combines arm- and foot-powered recumbent cycling in the front with a standard bicycle in the back. The back rider steers through a remote linkage from the handlebars to the front wheel, and pedals in a standard bicycling posture. The front rider sits in a recumbent position and powers with any combination of arms or legs.

Both riders have a clear view ahead and find it easy to converse. The front cranks directly couple, allowing the front rider to assist or passively exercise his or her own less functional limbs. For those who prefer not to move their legs, a leg rest attaches to the seat. A freewheeling system allows the front rider to rest while the back rider continues to pedal. If a rider is unable to pedal at all, he or she may just go along for a ride.

When the Sunburst comes to a stop, the front rider can lower a secure kickstand. The front drive system and seat can be detached, yielding a single rider bicycle. To increase the market, and to provide greater dignity for the disabled rider, the front position has been designed to appeal to able-bodied riders as well.

STATUS An improved Sunburst design (Figure 3) has been used for the construction of the first commercial version, completed in May, 1986, by Keith Bontrager, a custom bicycle frame builder in Santa Cruz, CA. Owners of this version of the Sunburst have enjoyed features such as gearing for the front rider and an improved kickstand. Layout and detail drawings of the Sunburst design

1. Spinal Cord Injury Center

were constructed using CADAM, a computer-aided-design software package running on an IBM 5080 color graphic workstation at the Stanford Center for Design Research.

A similar tandem, called the Counterpoint, developed independently of the Sunburst, is available from Counterpoint Conveyance Ltd., in Seattle, Washington. Individuals interested in the Sunburst may consider requesting features found on the Sunburst, such as the combined arm- and foot-power for the front rider and the secure kickstand, be incorporated in the Counterpoint design.

Figure 2. Sunburst, second prototype. Photo by Bruno Schlumberger.

ACKNOWLEDGEMENTS

Design and construction contributions were made by: Gordon Abraham, Keith Bontrager, Gary Hale, and Kate Hunter-Zaworski.

PUBLICATIONS

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Schwandt DF. Design development of arm-powered bicycles for the disabled. *SAE*, paper 840023, 1984.

SUPPORT

British Columbia Program for the International Year of the Disabled Person (1982-84)
University of British Columbia Athletic Department (1981)
Center for Design Research, StanfordUniversity
RR&D Core Resources

Figure 3. Sunburst, commercial version.

Michael Zomlefer, PhD
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Jeffrey Aldrich, Ind Des
James Anderson, Exp Mach
Russ Miller, BS

Optimal Biomechanical Design of Arm-Powered Mobility Devices

PROBLEM Individuals with lower limb disorders are looking for better solutions to their mobility and exercise needs. Through such improvements, they may enjoy the quality and degree of independence and societal integration to which they are entitled. Few alternatives to the handrim-propelled wheelchair are currently available, and little research has been done to fine-tune mobility aids to individual users. A need exists for ergonomically optimal arm-powered drive systems.

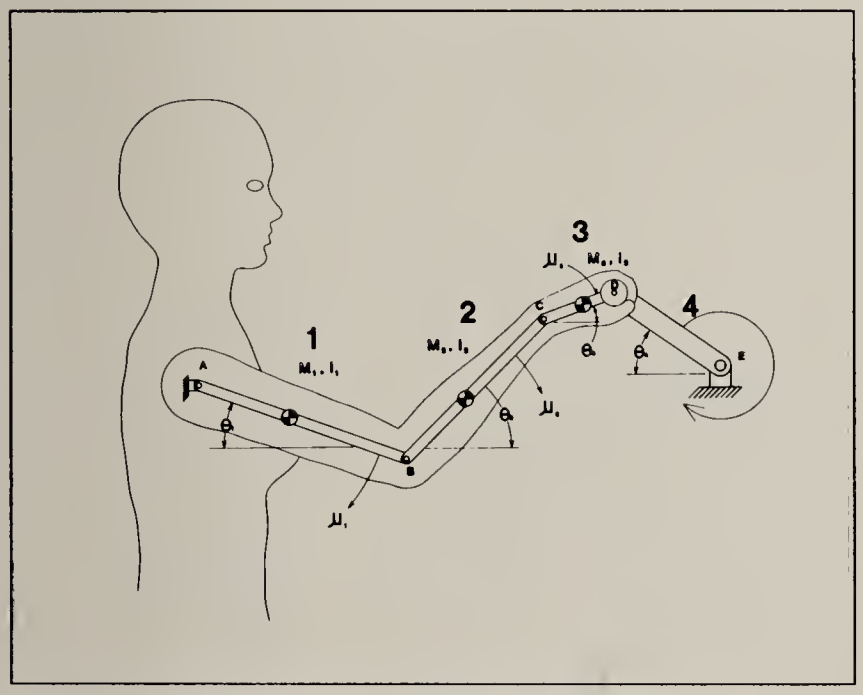

Figure 1. Biomechanical model of upper limb.

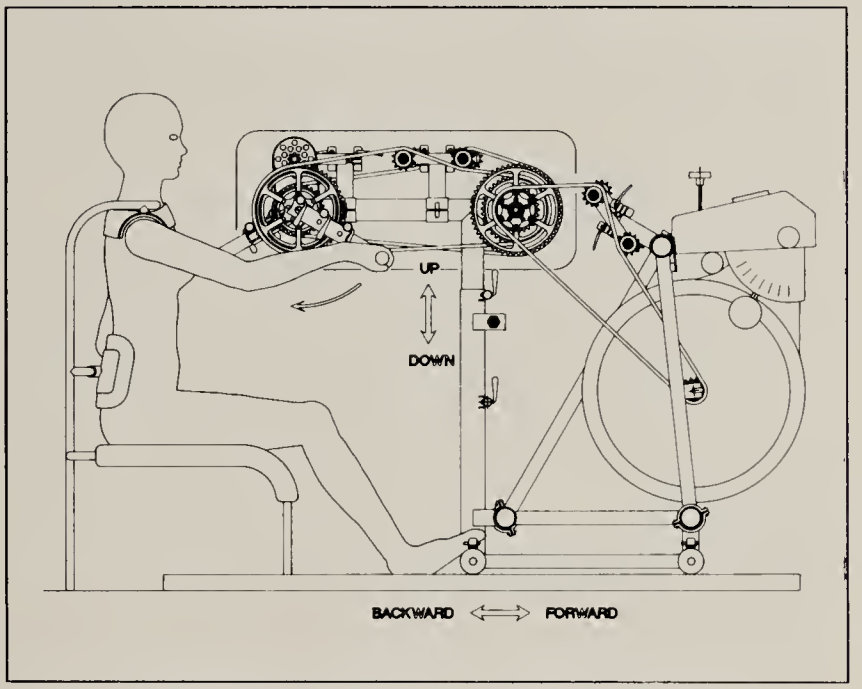

Figure 2. Modular rotary crank ergometer design.

SIGNIFICANCE The development of computer simulations of the upper limb will support the design of optimal arm-powered drive systems for mobility and exercise devices. The combined theoretical and experimental approach used in this study can be extended to other functional tasks such as reaching, grasping, moving, and manipulating objects. Better models for limb dynamics will also serve functional electrical exercise (FEE) and biofeedback strategies through improved understanding of muscle activation sequences.

BACKGROUND Modern optimal control theory has been used successfully for decades by the aerospace and military as an important engineering design tool to achieve optimal device performance. Using advanced computer modeling, engineers explore design changes quickly without resorting to expensive prototype re-engineering. Attempts have been made to apply these modeling techniques to biological systems, as in modeling human locomotion and jumping.

HYPOTHESIS Modern control theory, when coupled with human biomechanical performance measurements, can lead to nearly optimal arm-powered drives for use in mobility vehicles and stationary exercise machines for the disabled. This involves the development of a biomechanical computer model for the upper limb during arm-propulsion tasks. Given specified performance criteria (such as maximum power output or maximum efficiency), this model may be used to compute optimal specifications for any proposed drive system.

APPROACH The experimental results obtained from subjects operating arm-powered ergometer drive systems will be used to refine the biomechanical model of the upper limb (see Figure 1). In order to develop a more universal model, several drive and load systems will be em-

ployed, each with such variable features as crank length for arm cranking experiments (Figure 2), or lever length and pivot position for oscillating lever propulsion. Kinematic and dynamic data will be acquired (Figure 3), and analyzed with simultaneously collected electromyograms (EMGs).

STATUS The laboratory arm-powered ergometer has been designed, built and instrumented. Initial experiments are underway in the Biomechanics Laboratory at Santa Clara University with able-bodied subjects. Additional experiments will follow with paraplegic subjects, and results will be analyzed to validate the computer simulations.

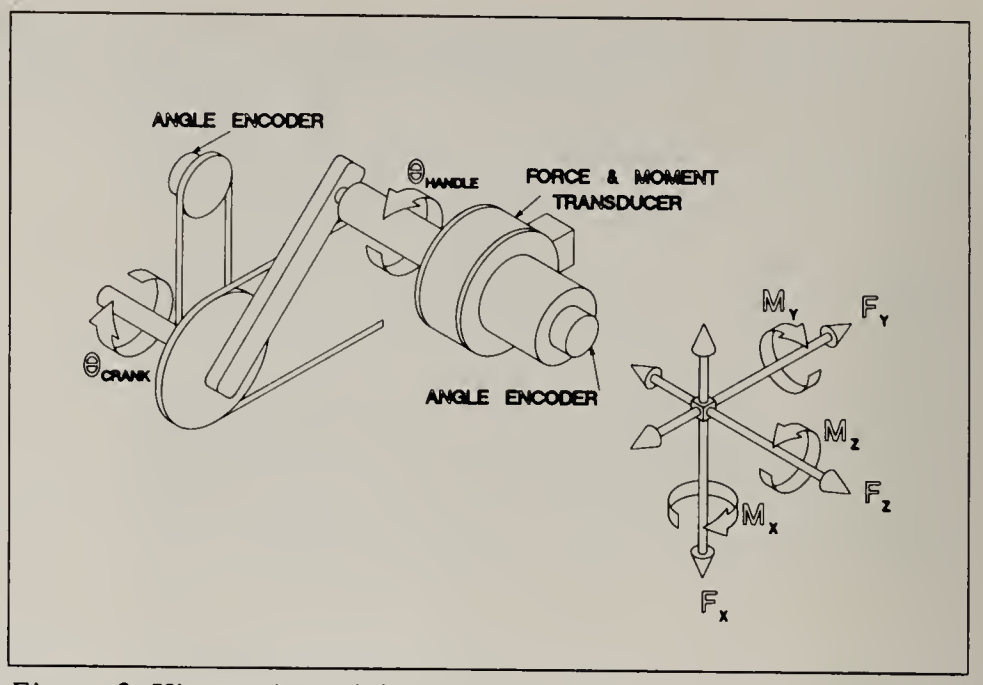

Figure 3. Kinematic and dynamic data instrumentation.

ACKNOWLEDGEMENTS

In addition to those mentioned above as authors, other contributions to the design, construction, instrumentation and analytical equations of motion have been made by: Keith Bontrager, Tim Hight, Linda Hollis, Jason Lee, and Eric Reid.

PUBLICATIONS

Schwandt DF, Aldrich JC, Zomlefer MR. A modular multiple drive/load ergometer for the development of an optimal biomechanical model of the upper limb. *Proc 9th Ann Conf Rehabilitation Technology (RESNA)*, Minneapolis, MN, 5: 427-428, 1986.

SUPPORT

Center for Design Research, Stanford University
Santa Clara University
VA RR&D Merit Review (1985-87)
RR&D Core Resources

David L. Jaffe, MS
Janice McKinley, MA[1]
Steve Shindell, PhD[1]

A Voice-Output Questionnaire Administrator

PROBLEM There is a recurring need to assess the effectiveness of the VA's clinical rehabilitation programs. In particular, blind rehabilitation programs face unique problems in responding to this need because commonly used techniques such as printed questionnaires and surveys are not appropriate for a visually impaired population. Alternate techniques, such as staff/veteran interviews, are very time consuming and prone to human bias and error.

SIGNIFICANCE This project aims to develop an automatic system for collecting questionnaire data from blind and visually impaired individuals. The system will greatly reduce the amount of staff personnel time needed to administer questionnaires, which is expected to result in more frequent testing and hence more accurate assessment of program effectiveness. In addition, the results obtained from the proposed computerized testing are anticipated to be more accurate in their own right than those obtained from an interview, since any human bias in asking the questions, recording the responses, and scoring the answers will be eliminated.

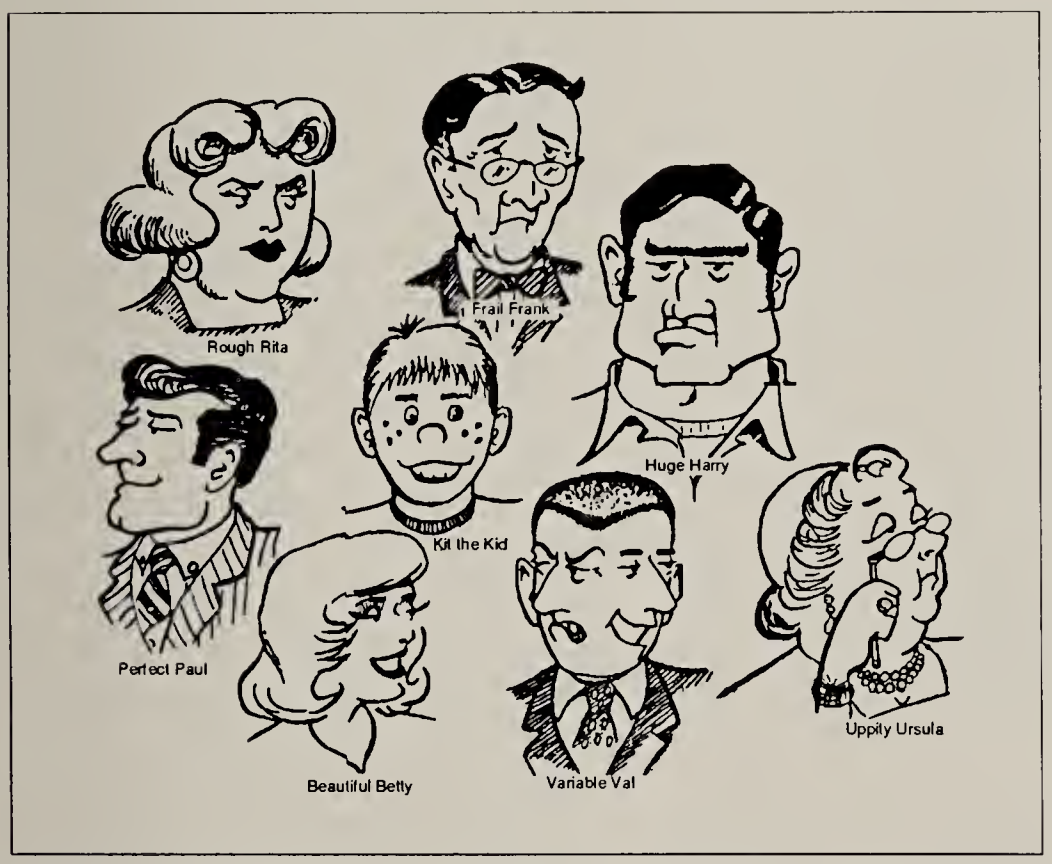

Figure 1. Personification of synthetic voices available with DECtalk.

BACKGROUND A long-standing need at the Western Blind Rehabilitation Center is to insure that its rehabilitation program is effectively meeting the needs of the veteran. One measure of that effectiveness is to monitor the veteran's mental condition during the course of his/her training and rehabilitation. Ideally this should be done on a daily basis. However, traditional techniques including verbal presentation, telephone surveys, and printed or taped questionnaires consume excessive staff time, are inappropriate to administer to visually impaired veterans, or are too costly and complex. For those reasons, they have not been routinely done.

HYPOTHESIS This project employs a computer-controlled DECtalk speech synthesizer to administer, score, display the results of, and maintain data from a standard psychological test (POMS, the Profile of Mood States) for visually impaired and blind individuals under the care of the Western Blind Rehabilitation Center.

APPROACH To measure and compare the mental state of individuals, the Bipolar form of the POMS has been developed by the Educational and Industrial Testing Service to quantify six selected bipolar subjective mood states. In this test, each mood consists of two extremes, one represented by the positive aspects of the mood, the other by the negative aspects (such as happy-sad). Each of the six moods (composed-anxious, agreeable-hostile, elated-depressed, confident-unsure, energetic-tired, and clearheaded-confused) are measured by analyzing the test-taker's level of agreement to positive and negative mood indicator phrases such as "cheerful" or "downhearted". While POMS was developed to evaluate established mood states and feelings reported by both normal and psychiat-

1. Western Blind Rehabilitation Center

ric patients, the principal contemplated use of this test at the Western Blind Rehabilitation Center is to evaluate the relative effectiveness of various training programs in reducing negative moods while enhancing the positive ones.

The POMS test can not be administered in the traditional manner to patients who are blind or have visual impairments since neither group has the visual acuity to read the individual phrases, nor the ability to indicate their choice on the answer sheet. Currently, a staff member reads the phrases to these individuals, queries them for their response, and then fills in the appropriate box on the answer sheet. Later, he or she scores the answers by hand and graphs the results. The entire task can take twenty minutes, a length of time that does not easily fit into the staff member's busy schedule. Computerized administration and scoring of the questionnaire, on the other hand, would reduce demands on staff time to about five minutes per test.

We have developed a prototype question administration system that consists of an IBM-XT computer with printer, a DECtalk speech synthesizer, and appropriate software. The DECtalk unit has been chosen because it produces speech that is readily understood by those with no computer experience.

During test administration, the computer first provides verbal instructions to the test-taker and then proceeds to present each mood phrase in turn and ask for a response. The user responds by either pressing a key on a standard keyboard or one of a set of large mushroom-shaped buttons. If, after a given time, no response is made, the computer re-issues the phrase. The system confirms all responses, and the user can change an answer if a mistake is made. At the completion of the test, the computer scores the results and computes a dated graph of the mood state profile. This graph can be compared to others taken previously and is eventually placed in the user's medical record.

STATUS The initial software phase of this project has been completed. The first volunteers and test subjects have been selected and testing has begun. At this early stage, no conclusions can be made as to the accuracy or repeatability of this voice-output method of testing.

Two positive results are anticipated upon completion of the pilot phase of this project. First, the project will provide the Western Blind Rehabilitation Center with needed data concerning the effect of the courses and therapy it provides to its patients. Second, it will provide information on the utility of computer-based speech synthesizers in administering psychological tests to visually impaired and blind individuals. This data should also prove useful in the development of other systems that disseminate information over the telephone using a speech synthesizer.

PUBLICATIONS

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Jaffe DL. A voice-output questionnaire administrator. *Proc Voice I/O Sys App Conf,* Alexandria, VA, 1986.

SUPPORT

Digital Equipment Corporation
Western Blind Rehabilitation Center
RR&D Core Resources

James Kramer, MS
Larry Leifer, PhD

The Talking Glove: a Communication Aid for Deaf, Deaf-Blind, and Nonvocal Individuals

PROBLEM While many deaf individuals communicate effectively with other deaf individuals using a form of sign language or the fingerspelling alphabet, problems arise when a hearing person who does not know sign languag, attempts to interact with a deaf individual who does not know the "oral" method, *i.e.*, cannot speak intelligibly and read lips. For deaf-blind individuals, communication is even more difficult since they must be able to touch the hand of the person with whom they wish to interact.

SIGNIFICANCE Communicative limitations adversely effect interpersonal relationships as well as vocational activities. Many deaf, deaf-blind, and nonvocal people avoid situations requiring social interaction with hearing persons. Consequently, many of these individuals remain unemployed and dependent, and cannot fully participate in community life. Thus, there is a great need for a portable communication aid which would permit deaf, deaf-blind, and nonvocal people to engage in conversation among themselves and with hearing persons.

BACKGROUND Several communication devices, most notably the Telecommunications Device for the Deaf (TDD), Telebraille, and Tellatouch, have been developed to assist people with hearing or speaking disabilities. Each of these devices has limitations. The TDD and Telebraille are used by deaf, deaf-blind and nonvocal individuals for telephone communication but are not efficient for two-way personal interaction. The Tellatouch takes keyboard input from a hearing person and displays it as braille for a deaf-blind individual to read, but it does not incorporate any features which enable the nonvocal deaf-blind person to respond. Note writing is commonly used by sighted, nonvocal individuals to communicate with someone who is nearby. However, notes do not work at a distance or when more than two persons must participate in conversation. The TDD, Telebraille, and Tellatouch are not designed for use while walking or standing and are impractical for daily encounters at a store, restaurant, or bank.

HYPOTHESIS A portable communication system, based on the concept of a "talking glove" will greatly reduce the communication barrier between hearing people and deaf, deaf-blind, and nonvocal individuals. The system will consist of an instrumented glove to sense sign language gestures, and a pattern recognition algorithm to translate these gestures into speech.

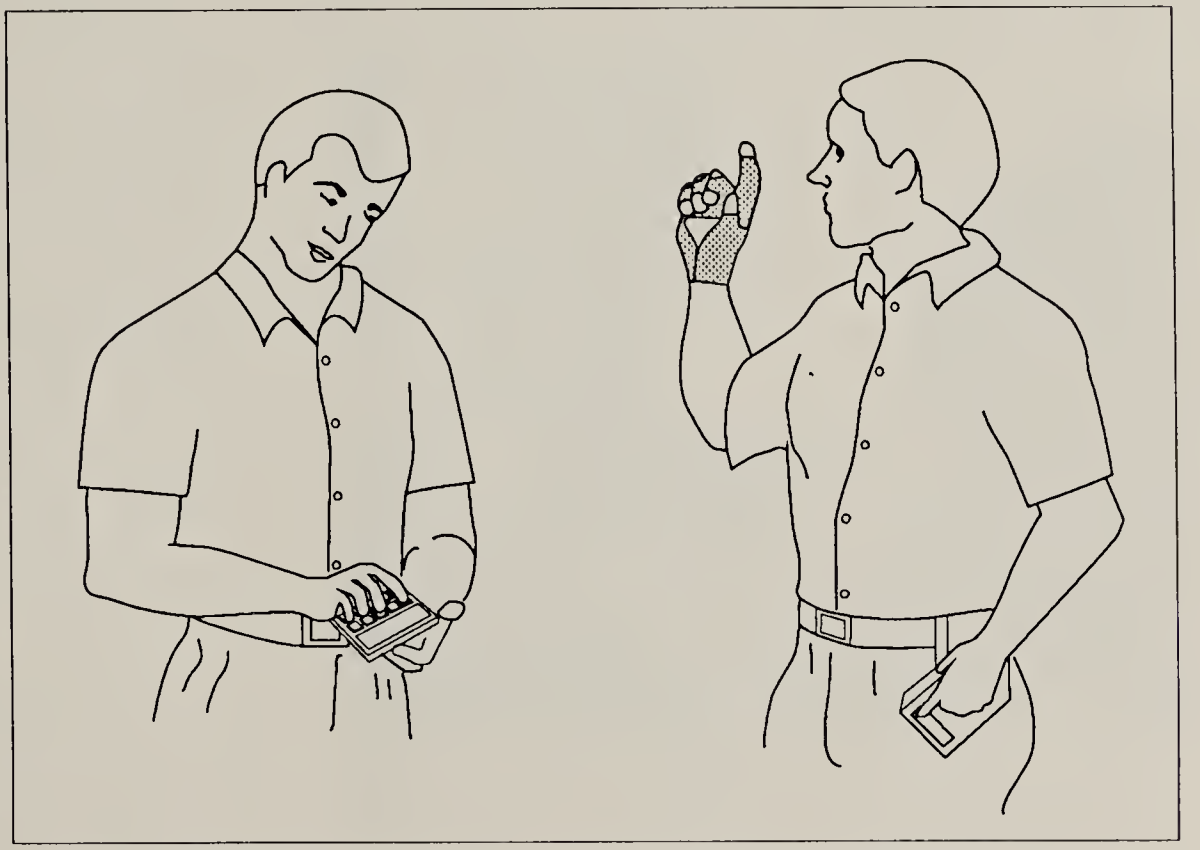

Figure 1. Proposed method of communication: at left, the hearing person uses a wireless keyboard and display unit; at right, the deaf-blind person uses the talking glove.

APPROACH The proposed two-way communication system consists of a portable data-processing module and

various user-selectable peripheral devices. These peripherals will be chosen to transmit and receive information based on the individual's specific communication requirements.

Figure 1 shows how a nonvocal deaf-blind user would transmit synthesized speech to a hearing person. The nonvocal person (Figure 1, right) would perform a Signed-English sign or fingerspell while wearing a glove equipped with sensors. This instrumented glove would supply hand-formation and motion information to a recognition algorithm which would identify the intended gesture. Once a signed or fingerspelled word is determined, the processing module would send the data to a speech synthesizer and the corresponding word would be spoken to the hearing person via a miniature speaker worn as a "speech pendant" under the shirt of the nonvocal individual. In effect, the nonvocal user's information output device would be a "talking glove".

To permit a hearing person to transmit a message to a deaf user, a pocket calculator-size wireless keyboard is proposed (Figure 1, left). The wireless keyboard could be carried in the shirt pocket of the deaf or deaf-blind individual and handed to the hearing person with whom he or she wanted to communicate. The small keyboard would have a liquid crystal display (LCD) that could state the deaf person's name and request message input from the hearing individual. Data entered on this keyboard would be transmitted to the data processing module via a wireless infrared or radio link and displayed for the deaf person.

Text generated by the hearing person using the pocket keyboard could be displayed for the deaf individual in a variety of ways. For sighted deaf people, text could be displayed visually on a small LCD monitor worn as a wristwatch. A deaf person with reduced vision might require that the text be output on a large-print LED (light-emitting diode) display. For a deaf-blind user, the text could be sent to a portable multicell mechanical braille display. The proposed braille module would fasten to the belt for use while walking and standing but detach for desk-top use.

STATUS A prototype communication system has been developed which gives synthesized speech capabilities to a nonvocal deaf or deaf-blind person. The arrangement uses a DataGlove (an instrumented glove produced by VPL Research) to supply hand formation data to a recognition algorithm which identifies the intended letter of the fingerspelling alphabet. When the letters of a word are recognized, the entire word is spoken to the hearing person by a DECtalk speech synthesizer.

The hearing person can respond to the deaf user by typing a message on an IBM PC/AT keyboard. An Intro-Voice voice recognition system has also been integrated which allows trained individuals to send a message directly by speaking. Sighted deaf persons read the entered message on a small Seiko LCD display worn on their wrist. A deaf-blind user reads the information tactually on a refreshable mechanical braille display.

The prototype communication aid has been tested by several deaf-blind and nonvocal-deaf users, and the results are encouraging. Interaction with these individuals has been valuable to the design thus far and will be maintained throughout the development to ensure that the final product incorporates the needs and desires of its potential users.

PUBLICATIONS

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Kramer J, Leifer L. An expressive and receptive communication aid for the deaf, deaf-blind, and nonvocal. *Proc 9th Ann Conf IEEE Eng Med Bio Soc*, Boston, MA, 1987.

SUPPORT

RR&D Core Resources

Deborah Gilden, PhD[1]
David L. Jaffe, MS

Dexter, a Robotic-Hand Communication Aid for the Deaf-Blind

PROBLEM People who are both deaf and blind experience extreme social and informational isolation. Many deaf-blind individuals enjoy some relief from this isolation by using a "hands-on-hands" version of fingerspelling or sign language to converse with others. This tactile method is far from ideal, however, as it requires that the other person know fingerspelling or sign language and be willing to engage in this hands-on-hands technique. In addition, it is both a fatiguing and tedious method of communication.

SIGNIFICANCE The goal of this project is to design a communication device that will allow deaf-blind users to receive information from a variety of electronic sources. This will open many important communication channels, including face-to-face conversation with non-signers via keyboard input, telephone communication via TDD, and television programming via closed-caption capture devices. Access to computer data bases that could provide improved vocational and avocational potential to the deaf-blind community will also be provided.

BACKGROUND A common communication technique used by deaf-blind people is a combination of a hands-on version of fingerspelling and/or sign language. Instead of receiving communication visually as deaf people do, the deaf-blind person's hand (or hands) remain in contact with the hand (or hands) of the person who is fingerspelling or signing. Many of the motions used in sign language involve both hands and arms and are therefore poorly suited for tactile communication. Instead, each word is typically spelled out, one letter at a time, using the fingerspelling technique. Although many Usher's syndrome patients can speak intelligibly or use sign language, other deaf-blind individuals require a "hands-on" system for expressive communication.

HYPOTHESIS A potential solution to this communication problem is offered by a computer-based, pneumatically powered, electro-mechanical fingerspelling hand. It enables a deaf-blind user to receive tactile messages from the mechanical hand in response to keyboard input during person-to-person communication, as well as to gain access to local and remote computers and the information they contain.

APPROACH The Rehabilitation Engineering Center of the Smith-Kettlewell Eye Research Institute sponsored a class project conducted by four graduate students in the Department of Mechanical Engineering at Stanford University to design and fabricate a state-of-the-art fingerspelling hand. A major goal was to develop a system with controlled timing and easily modifiable finger positions. These qualities were realized in the completed project—a new robotic fingerspelling hand named "Dexter".

Figure 1. Deaf-blind user receiving a message through Dexter.

Dexter looks like a mechanical version of a rather large human hand projecting vertically out of a box. The four machined aluminum fingers and a thumb are joined together at a palm. The digits operate independently and have a range of motion comparable to human fingers. The thumb is jointed to allow it to both sweep across the palm and to move in a plane perpendicular to it. A pneumatic rotary actuator allows the palm to rotate around a vertical steel rod much the way a human hand can rotate

1. Smith-Kettlewell Eye Research Institute

at the wrist—except that a full 180 degrees can be achieved by Dexter. Downward flexion, however, is not currently possible.

All finger and thumb motions are actuated by drive cables. Pneumatic cylinders pull these cables which flex the individual fingers and thumb, while spring-driven return cables open the finger joints to the extended position. The cylinders, in turn, are activated by air pressure directed through electrically controlled valves. These valves are controlled by a microcomputer system. The actuating equipment and valving are housed in two separate assemblies below the hand.

In operation, the microcomputer and associated software control the opening and closing of a bank of valves that direct air pressure to specific pneumatic cylinders which pull on the drive cables which are the "tendons" of the fingers. As a message is typed on a keyboard (an Epson HX-20), each letter's ASCII value is used by the software as a pointer into an array of stored valve control values. Since 22 valves are controlled, three bytes are required to specify the state of each valve (open or closed). Two to six of these valve operations, each separated by a programmed pause, are needed to specify the coordinated finger movements corresponding to a single letter. Presently, the hand can produce approximately two letters per second, starting from and returning to a slightly flexed neutral position.

Although the mechanical hand can not exactly mimic the human hand in fingerspelling all the letters (such as the special wrist and arm motions required in J and Z), modified versions of these can be used instead. On the other hand, an advantage of the mechanical system is that it always produces the same motions for a given letter.

STATUS Several deaf-blind clients of Lions Blind Center (Oakland, CA) served as subjects for the initial testing of Dexter. They were able to identify most of the letters presented by the robotic hand without any instructions, and in less than an hour were correctly interpreting sentences. Equally important was their positive emotional reaction to the hand. They enjoyed using it and were intrigued by its novelty. There were no negative comments about its mechanical nature or any other aspect of the system.

Additional testing will be conducted on the ability of deaf-blind people to use the robotic hand for extended periods of time, as well as on determining optimal configurations for the letters, and optimum rate of letter presentation. The possibility of modifying the one-hand manual alphabet to require only the thumb and first two fingers will also be investigated. Since the last two fingers are redundant for most letters of the manual alphabet, this may be a reasonable approach to reducing the size, weight, complexity, and expense of the system. In addition, it would make Dexter more like typical robotic hands (*i.e.*, those for manipulation of physical objects), which generally consist of three digits.

New methods for powering Dexter will also be investigated to eliminate the need for pneumatics and make the device more portable, a requirement for a commercial product. Bio-Metal, a shape memory material, is being evaluated as a potential substitute for the valves and cylinders in the present system.

In the next software design iteration, a finger position editing program will be written. This program will permit the interactive formation of letter-pair transitions. The valve control information resulting from this phase will be incorporated into the next evaluation of Dexter. The future implementation of a full 26 by 26 matrix of possible letter-pair transitions would eliminate the need for the intermediate neutral position and produce more rapid and natural fingerspelling. A faster and more intelligible fingerspelling device is anticipated.

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ACKNOWLEDGEMENTS

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SUPPORT

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The DataGlove: a Semi-Automated Hand-Function Evaluation System

PROBLEM Loss of hand function resulting from spinal cord, nerve, or tendon injury, arthritis, or fracture severely restricts a person's independence and ability to contribute to family and society. Three major problems in treating hand impairment are being addressed by this study:

(1) assessing the exact extent of the impairment,
(2) deciding the best therapy for the impairment,
(3) evaluating the results of therapy—whether by surgery or rehabilitation.

SIGNIFICANCE The cost to the American economy due to hand impairment is estimated to be $10 billion per year [1]. A substantial portion of this cost consists of medical and rehabilitative diagnosis and treatment, central to which is functional assessment. Present methods of hand evaluation are time-consuming, non-quantitative and static, lacking means for measuring position and force while the hand is in motion. New dynamic measurement and information processing modalities will improve collection of data from patients before and after treatment, and permit comparison of current performance with prior and projected capacity. The effects of tendon transfer surgery, hand therapy to improve range of motion, and external splinting can be evaluated using a library of normal and impaired hand motions.

BACKGROUND Present methods of hand evaluation can be divided into anatomic and functional categories[2]. Anatomic evaluations involve using a goniometer to measure range of motion of each joint and a force gauge to record strength of muscle groups acting across a joint. Sequentially recording each joint in several selected positions is tedious and requires extensive manual data entry.

Functional evaluation such as the Jebsen Hand Function Test [3] provides appraisal of loss of capacity as it relates to activities of daily living and the more common specialized manipulation tasks common to all persons. In the Jebsen test are seven "time-motion" subtests:

(1) writing,
(2) card turning,
(3) manipulation of small objects (bottle caps, coins, etc.),
(4) simulated feeding (picking up beans with a teaspoon),
(5) stacking checkers,
(6) moving and manipulating large light objects (empty cans),
(7) moving and manipulating heavy cans.

The patient's physician rarely participates in these tests due to the time required; the patient cannot perform the test at home since an occupational therapist must set up the subtests and record task times.

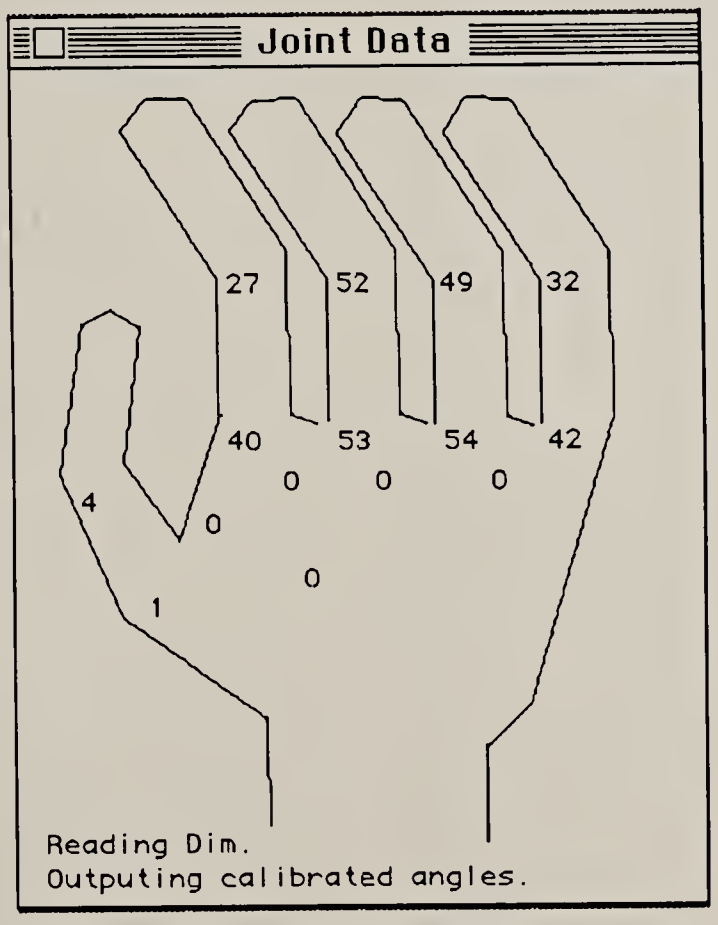

Figure 1. DataGlove computer display

HYPOTHESIS The development of a system to better assess hand function may help in deciding the best therapy and could improve the results of therapy by guiding the physician or occupational therapist in optimizing the care of patients with hand impairments. One component of such a system is the DataGlove (VPL Research Inc., Redwood City, CA) which looks and feels like an ordinary light fabric glove, but includes bend-

ing sensors connected to a computer. The computer uses the outputs of these and a separate spatial position sensor to calculate the angles of each finger joint and the overall position of the hand. It can display a picture of the hand with fingers bending to grasp and manipulate a real or simulated object, and additionally can tabulate position in near real-time (see Figure 1).

APPROACH The DataGlove will be used as part of a three-phase program to: (1) modify present software to better acquire data from abnormal hands, (2) record data from normal hands while performing tasks derived from the Jebsen test, and (3) evaluate patients suffering from several types of impairment due to high spinal cord injury, peripheral nerve injury, tendon injury. or arthritis.

Concurrently, research is being undertaken to: (1) improve upon the DataGlove's ability to detect finger and thumb ab- and adduction, (2) calibrate the DataGlove's calculated finger angles against an absolute standard, and (3) add force measurement capability to the system.

Among the force-measurement techniques being studied are the inclusion of pressure-sensing pads to the palmar side of the DataGlove and similar pads applied by the therapist external to the glove.

STATUS The DataGlove has thus far been used to gather single-finger bending-angle data on normal subjects. This portion of the study is being repeated for all five fingers, and compared to standard goniometric measurements for the resting position of each joint, the maximum active extension and flexion (opening and closing the hand) and maximum passive extension and flexion. A data sheet printed by the MacIntosh computer connected to the DataGlove is then compared to the manually-transcribed data sheet prepared by the therapist.

A series of hand-held force plates has been constructed and tested in a clinical setting for measuring lateral pinch, four-finger flexion, and wrist and elbow flexion/extension forces. An electronic package is being designed to automatically detect which of several force plates is in use, hold a maximum force value, and compensate for the non-linear output of the force sensors.

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SUPPORT

VA RR&D Merit Review (1987-present)

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Easy Access to Sources of Computer-Based Rehabilitation Information

PROBLEM In rehabilitation, the need for accurate and timely information is great. For example, consumers of rehabilitation devices, no matter what their disability, have to know what products will meet their needs. Design engineers have to be aware of the work of their colleagues in order to make efficient use of limited research funds and be aware of the needs of people who would use the new devices. Manufacturers have to form working relationships with developers to insure that the fruits of research reach the marketplace. Health care professionals have to recognize advances that would increase the quality of life for the patients they serve. And all segments of the rehabilitation community need to interact with each other despite (1) physical or sensory impairments, (2) geographic separation, (3) rehabilitation speciality, or (4) lack of computer equipment and expertise.

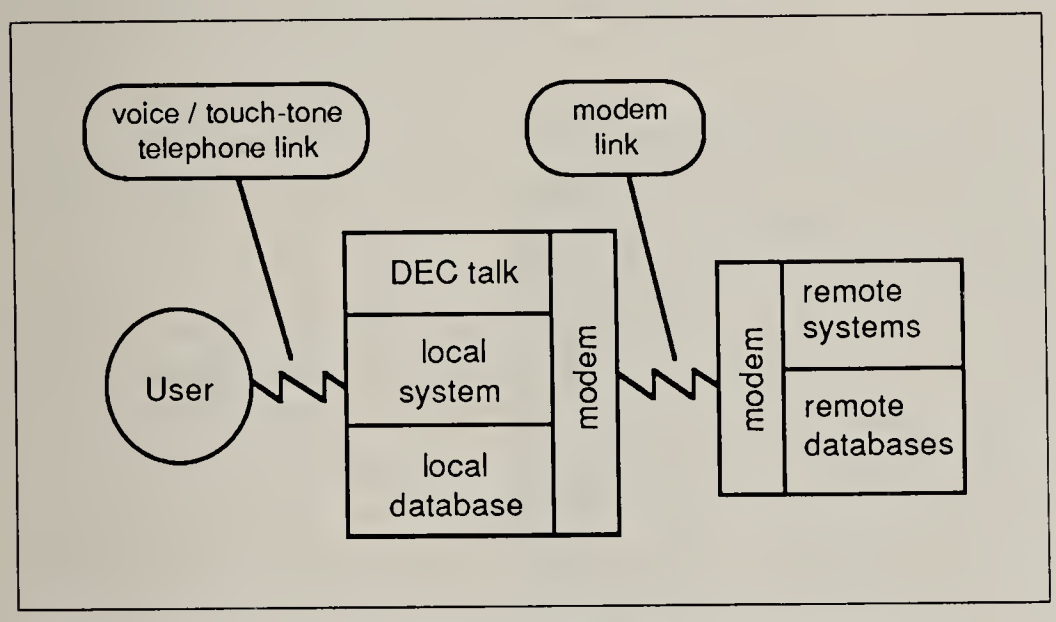

Figure 1. Block diagram of proposed transparent-access system.

SIGNIFICANCE A method of easy—or "transparent"—access to computer-based rehabilitation information makes it possible for members of the rehabilitation community without possession or knowledge of computers to obtain existing information and, in general, interact with one another. It does not require the purchase of or instruction in new equipment as it employs only existing and familiar devices: the telephone and its touch-tone keypad. The substantial barriers of having to buy and learn how use a computer for obtaining computer-based information would be eliminated. Both able-bodied and disabled people benefit equally from this type of access.

In summary, a system based on the concept of transparent access serves persons who are disabled because of their lack of information and those that are disabled because they lack the funds and time to buy and learn how to use a computer to connect to sources of computer-based rehabilitation information.

BACKGROUND Much rehabilitation information is already available on public and private databases or electronic bulletin boards on remote computer systems. This trend towards computer-based information is increasing. However, to reach the information contained in these 'storehouses', the information seeker must (1) employ computer hardware including a modem, (2) be educated in the use of the computer hardware and modem software, (3) be knowledgeable of the sources of computer-based information, (4) subscribe or otherwise connect to the particular computer-based information source, and (5) become proficient in the syntax of those source(s) of computer-based information in order to formulate a request for the desired information. If all these requirements are not met, the desired information can not be acquired. The need to employ computer hardware and software and the substantial knowledge of their use are, therefore, real barriers to obtaining any computer-based information.

HYPOTHESIS This project demonstrates methods that increase communication and minimize or eliminate the above equipment and expertise requirements from computer-based information acquisition. The essence of the approach is to employ a centrally located telephone-accessible computer system which (1) engages in a voice output, Touch-Tone input dialog with callers, (2) learns

of their information needs, (3) connects to the appropriate information source, (4) transparently acquires the information, and (5) presents it to the caller in voice output format. (Modem communication could also be incorporated, supporting individuals already owning computers, including those with hearing impairments.)

APPROACH A software program, KIOSK, has been developed that demonstrates how the barriers to obtaining computer-based information can be reduced, benefitting both able-bodied and disabled people.

The KIOSK software has been designed to run on either 8-bit or IBM-PC compatible computer systems. A DECtalk speech synthesizer completes the hardware complement and provides a friendly interface between the computer and its data and individuals requesting information.

In operation, the user employs his/her home or business Touch-Tone telephone to dial the number of the DECtalk speech synthesizer and computer system. The equipment answers the telephone and KIOSK then mediates the interaction between the caller and the computer; speaking to the caller in its synthesized voice while monitoring caller-generated Touch-Tone keypresses. The software (1) permits the DECtalk to speak computer-based text files, (2) receives data from the DECtalk on which Touch-Tone keys have been pressed by the caller, and (3) works with a knowledge of a structure for presenting the text information files.

In the current implementation, the interaction between the caller and the computer is accomplished through a series of computer-initiated speech output and caller responses. The user is presented with either instructions, information, or choices. The caller's response to a choice is made by pressing the Touch-Tone key corresponding to his/her selection. The DECtalk recognizes the keypress and causes the program to branch in an appropriate manner based upon the response. This process is continued, with the computer sending information from text files to the DECtalk which are spoken over the telephone and the user making choices on how the interaction is to proceed. For example, a typical choice might be: press 1 for information on recreational devices, press 2 for information on robotic applications, or press 3 for information on new wheelchair developments.

KIOSK has been developed as a general-purpose program. It operates by structuring disk-based text files, presenting them verbally to the caller at the proper time, when the right sequence of choices has been made. The information provider designs this structure and provides the text files to be spoken by the program. As such, KIOSK is a flexible Authoring System for the DECtalk speech synthesizer and can be used to disseminate a variety of information.

STATUS One current application being demonstrated at this facility is a voice-output version of this Center's 1986 Progress Reports, which are printed descriptions of the operation of the Center and its projects.

When called, the system welcomes the user and briefly describes its operation. After a short introduction to the Center, the user is asked to indicate which of the three groups within the Center (Orthopaedic Biomechanics, Neuromuscular Systems, or Human-Machine Interface) he/she is interested. The user responds with a Touch-Tone keypress and the program branches to the information and projects of the chosen group. The title of a project is then presented and the caller is given the choice of whether to hear the text of the project, go on to the next project, or return to the previous menu of choices.

The KIOSK software has recently been used to create an information system serving blind athletes during their 1987 World Series of Beep Baseball at Ithaca College in New York. Competitors used their telephones to hear team scores and standings as well as information on how to get around campus and the immediate area. Listings of restaurants, shopping areas, bus schedules, and tourist attractions were all included.

The next extension of this work will allow a computer system to mediate the exchange of information between the caller and the information contained in remote databases such as CompuServe or computer-based bulletin boards systems. This would be accomplished by first engaging in a dialog with the caller to determine the information required and then connecting to the appropriate information source. Next, the computer would send the required commands in the proper syntax to obtain the information from the remote system and present it to the user as synthesized speech. An electronic librarian would thus be created to transparently search multiple databases of electronic information for the caller.

SUPPORT
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Computer-Aided Visual Communication for Severely Impaired Aphasics: Project Overview

PROBLEM Aphasia is language impairment acquired in adulthood from brain damage. Approximately 80,000 persons per year become aphasic, due chiefly to stroke or to vehicular accidents. While many recover partially or completely, around 20,000 each year are left with severe, permanent communicative disabilities. Many of these persons are unable to read, write, speak, understand, learn sign language, or otherwise use language to communicate. As a result, they are profoundly isolated from communication with others. For such *chronic globally aphasic* people, the traditional treatments of speech pathology do not lead to improved language or communication function. Many are placed in nursing homes, while others are returned to home care with family or other caregivers. Lacking effective means of communication and often confined to wheelchairs, they require much looking after. A treatment which opens up broader channels of communication for them could improve the quality of their lives, allow them greater freedom, and reduce their need for full-time nursing care.

Figure 1. C-VIC 1.0 on the Macintosh computer.

SIGNIFICANCE The successful development of this alternative communication device for severely impaired aphasics will: (1) enlarge the arsenal of tools available for aphasia rehabilitation; (2) make speech therapy more efficient and effective for the target population; (3) increase independence, and improve the quality of life following treatment for severely impaired aphasic persons; and (4) improve the cost-effectiveness for both the treatment and long-term care which must be provided for these patients.

BACKGROUND Research conducted in Boston in the mid-70's showed that many severely impaired aphasic individuals could learn to use an alternative communication system based upon pictures drawn on index cards, and that its use improved communicative function [1]. The system was called the VIsual Communication, or VIC, system. Trainees who were successful were able to use the system to ask and answer simple questions, give and receive simple commands, understand simple descriptions, and express simple wants and feelings. Although expressly designed to be a rehabilitative system, the VIC system did not transfer to everyday life outside the clinic. Among other things, it was cumbersome to use and limited in scope, needing greater communicative power across a range of situations to be practically useful to globally aphasic patients.

HYPOTHESIS Contemporary computer technology, used to build upon and extend ideas developed in the original research, can allow researchers to design and demonstrate a practically useful alternative communication system for globally aphasic individuals. The system currently under development is called C-VIC, for Computer-aided VIsual Communication. It is implemented on an Apple Macintosh computer, which features a high resolution text-graphics display, a window-based interface, control via the "mouse" pointing

device, and advanced devclopment tools for visual interactions and Artificial Intelligence (AI) modules. Advantages uniquc to the computer include: (1) multi-modal prescntation, including pictorial, audio, print text, and voice output; (2) interactivity, allowing the computer to provide helpful feedback, cues, or othcr assistancc; (3) animation, scaling, and entirc scene presentation; (4) programmability, to prcpare the systcm specially for upcoming situations; (5) natural language translation; and (6) automatic documentation, record-keeping, and reporting capabilities.

APPROACH Thrcc coordinated lines of investigation are bcing pursued in this project: clinical training, expcrimcntal clinical research, and advanced interface develop-mcnt. Each of thesc areas provides information that helps focus activity in thc other two. In our clinical training program, we have workcd with approximatcly ten severely impaired aphasic individuals, training them in systcm usc and monitoring their progress in system mastery (see Report 60). Areas of particular difficulty become candidates for targeted study in our experimental investigations, which employ rigorous experimental control within the framework of single-subject experimental study dcsigns (see Report 61). Techniques for improving performance which emerge from these studies prövide new material for assisting the design of subsequent interface versions. They are incorporated into interface research and devclopment, following which the new versions of the interface arc introduced back to the clinical training program to provide materials for further study.

STATUS Vcrsion 1.0 of the interface was completed in early 1987, and has been in clinical use and testing for a year. That vcrsion rcpresents an initial computer implementation and extension of the card-based concept, and is constructed primarily around the metaphor of decks and cards. Studies conducted with this interface have dcmonstrated that severely impaired aphasic individuals: (1) can master the operation of a complex, hierarchically organized, window based interface; (2) benefit from the use of the "mouse" pointing dcvice; (3) respond enthusiastically to working on the system; (4) use it to support communicative transactions at a level cxceeding their abilitics in natural English; (5) bcnefit from support provided by the system in executing complex tasks, such as rccipe preparation; and (6) show some modest ability to instruct themselvcs in the use of the systcm in certain contexts.

Version 2.0 of the system was completed in early 1988, and includcs powerful additional capabilities that hold promise of bcing useful, such as multi-modal presentation, interactive feedback, animation, scenes, programmability, and self-documentation, among othcrs. It is currently being introduced into clinical tcsting. A follow-on proposal is being prepared for submission to Rehabilitation Research and Development Merit Review to support the research and development of targeted applications, associated monitoring tools, and mechanisms for dissemination.

In the 1987 Annual Competition sponsored by the Inter-Agency Committee on Information Resources Managcmcnt, the principal investigators on this projcct, Richard Steele and Michael Weinrich, rcccived special awards for Creative / Innovativc use of microcomputers, for the design and implemcntation of this alternative communication system.

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SUPPORT

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Computer-Aided Visual Communication for Severely Impaired Aphasics: Clinical Training

PROBLEM Speech therapy has been shown to be effective in improving the communicative abilities of many aphasic patients [1]. However, a large number of those treated continue to exhibit significant residual aphasia after they cease to improve in therapy [2,3]. Patients with severe language deficits that are no longer responsive to therapy are in need of an alternative means of communication. Alternative communication devices presently on the market are designed primarily for persons with motoric deficits and cannot be used by aphasic persons whose primary deficit is impaired ability to employ the symbol system of spoken or written language. Past attempts at providing aphasics with a picture-based communication system have shown promise, but are limited and cumbersome for development and use outside of therapy [4]. Without sufficient natural language skills or an alternative communication system, aphasics suffer loss of independence and lowered quality of life.

SIGNIFICANCE C-VIC (the Computer-aided VIsual Communication system) shows promise as an alternative means of communication for aphasics (see Report 59). Patients trained on the system have been enthusiastic about it and are able to achieve communication competence levels that exceed their natural language abilities. C-VIC can be tailored to the specific needs of each patient: one patient might use it to communicate about activities of daily living while another patient uses recipes translated into C-VIC to cook safely and independently. C-VIC may also improve and/or expedite speech therapy: aphasia rehabilitation often relies on using stronger abilities to boost weaker ones, and C-VIC can serve as a stronger ability to help support natural language skills.

BACKGROUND Clinical training and clinical investigations represent a crucial component in the C-VIC R&D program. Those features which have consistently characterized our training with all patients include: (1) an educative (rather than a restorative) view on the way in which the system can be most useful; (2) a specified hierarchy of successively more difficult tasks introduced; (3) a relatively naturalistic approach to interacting with the subjects in which C-VIC may supplement spoken English in transactions; (4) deliberate switching between various tasks during training periods to emphasize the range of possibilities and to maintain patient interest; (5) periodic use of tests to check the subjects' accuracy, reliability, and confidence in using the system; and (6) the use of special adaptations of standard rating scales to assess performance in our system.

During training, subjects' performance is monitored periodically to establish the direction and rate of changes. When it is valuable to establish scientifically just what is responsible for effects noted, the researchers employ single-subject experimental study designs in more targeted work with the patients (see Report 61).

Figure 1. Clinical work on the C-VIC system.

Thus, clinical work in this project entails not only staff teaching the patients how to use the C-VIC system, but also results in the patients—through their participation in

scientific studies—teaching the staff how the system itself can best be designed, trained and employed.

HYPOTHESIS (1) By selecting goals which are useful and understandable to patients, and by utilizing computer technology to help reach these goals, the investigators aim to develop the C-VIC system into a powerful assistive device for use by aphasics—either as a general communication aid or as a guide in the performance of specific tasks. (2) Because C-VIC skills are superior to natural language skills for many chronic aphasics, the C-VIC system may serve as an effective rehabilitation tool. It can provide aphasics with a functional communication system that can ultimately help support improved communication in using natural language.

APPROACH Patients are presently being trained on C-VIC in both the hospital and home settings (see Figure 1). Training and data collection are focused in three directions: (1) re-establishing functional communication by substituting C-VIC for natural language; (2) tailoring C-VIC to assist patients in recovering specific skills which may otherwise be unattainable in aphasia, such as cooking; and (3) investigating the utility of C-VIC as a tool for rehabilitating natural language skills by providing a relatively intact and functional modality to boost natural language performance.

STATUS Nine subjects have participated in training for the purpose of using C-VIC as an alternative system for general communication. All patients have been able to exceed natural language skills using C-VIC. One patient who is unable to comprehend simple written recipes can successfully prepare these same recipes when they are presented in C-VIC (see Figure 2). The use of C-VIC in rehabilitation of natural language skills is presently being investigated with three patients.

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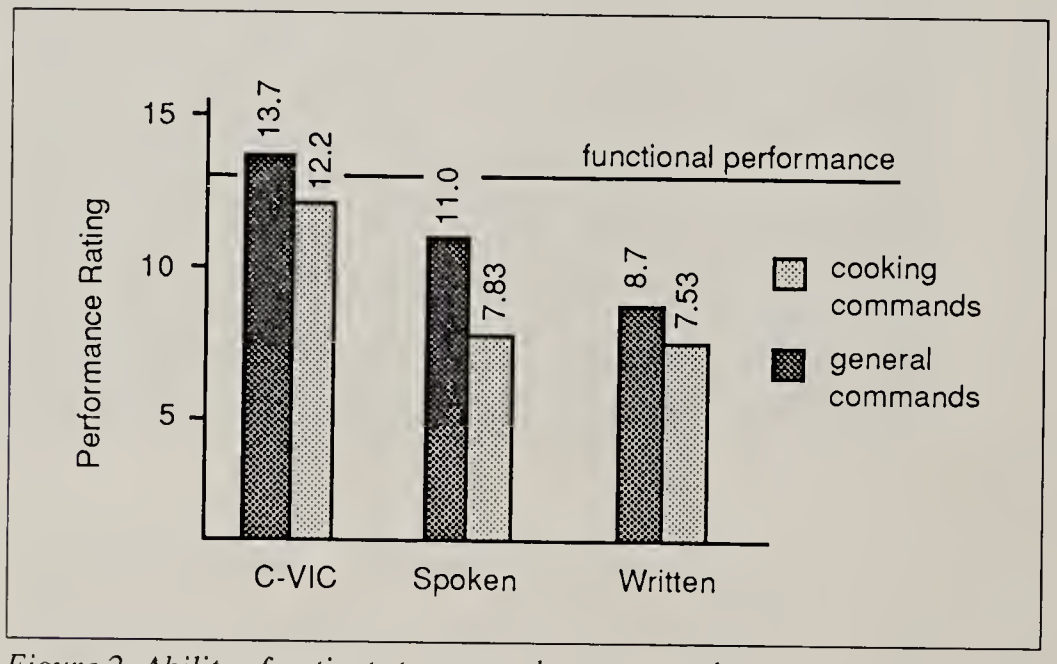

Figure 2. Ability of patients to respond to commands.

SUPPORT

Apple Computer Corporation
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VA Neurology Service
RR&D Core Resources

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Computer-Aided Visual Communication for Severely Impaired Aphasics: Experimental Study Designs

PROBLEM The investigators are seeking to develop a Computer-aided VIsual Communication (C-VIC) system, which will assist severely impaired aphasic persons to communicate more effectively (see Report 59). In order to do this, they need to investigate the communicative competence and the intellectual capacities of such patients, seeking in particular to identify and characterize the undamaged mental abilities which these patients can use in order to employ this powerful computer-based alternative communication system.

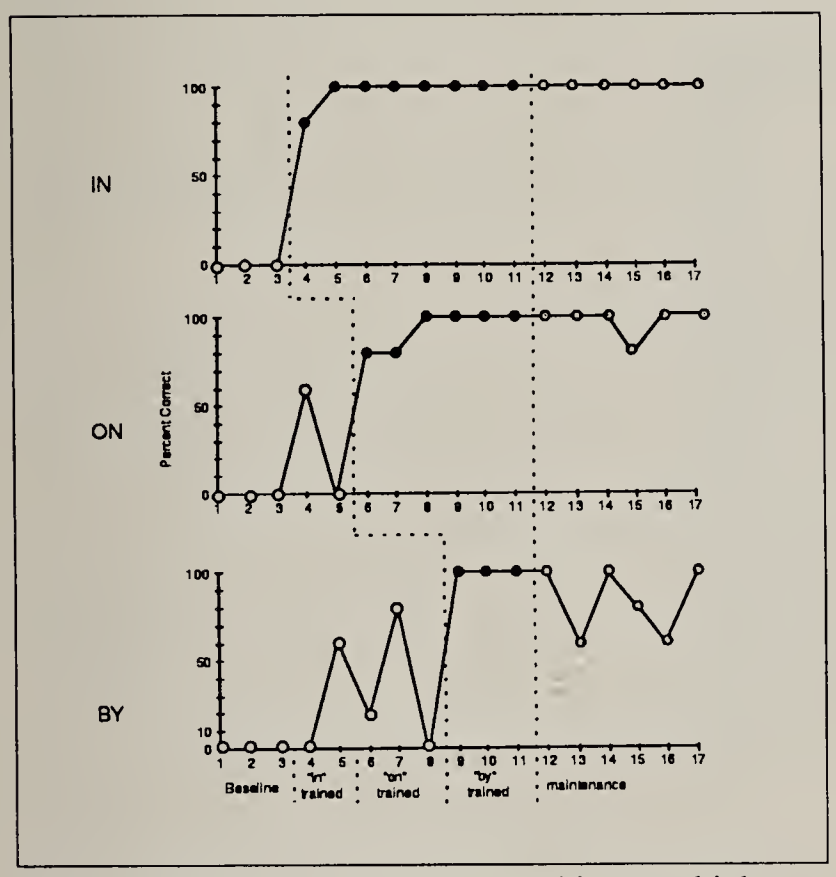

Figure 1. Receptive learning of prepositions, multiple baseline design. (Subject JS.)

SIGNIFICANCE The rationale for this particular work is twofold. First, a description of the residual capacities of severely aphasic patients is necessary for the intelligent design of alternative and augmentative communication systems for such patients. This information will provide the theoretical basis for improving the design and operational features of more advanced versions of the C-VIC system.

Second, the precise language deficits and processing problems such patients face have been studied intensively to provide clues to the mechanisms for language processing in normal individuals. Studies of the symbol use and comprehension of severely aphasic patients using an alternative communication system (which is not dependent upon words) may shed new light on results obtained in studies using natural language.

BACKGROUND Until the work of Jakobson [1,2] and Chomsky [3] in the 1950s and 60s, the investigation of the deficits and residual capacities of aphasic patients relied largely on clinico-pathologic correlations and broad psychological concepts. In the last thirty years, however, there has been increasing use of linguistic theory to analyze the speech of aphasic patients, and a sophisticated repertoire of neuropsychological techniques has been established. Such investigations have been difficult to conduct with most severely afflicted patients because of their limited abilities to comprehend and follow directions. Indeed, many early neurologists were of the opinion that severely aphasic patients could not think.

While more recent investigations with simple visual communication systems effectively refuted this contention and pioneered the way for more effective communication systems, they did not investigate the residual intellectual capacities of these patients in any principled way and especially not in regard to contemporary issues in neurolinguistics [4]. We have made use of the Computer-aided VIsual Communication (C-VIC) system developed at the Palo Alto VA Medical Center to investigate some contemporary issues regarding the intellectual capacities of severely aphasic patients.

HYPOTHESIS Our three hypotheses investigated during the course of this study were: (1) Even severely aphasic patients retain the ability to manipulate visual symbols according to abstract, syntax-like rules. (2) Such individuals can make use of a hierarchical organization of symbols. (3) Appropriate use of the alternative representation modes available on the computer screen can

improve patients' comprehension and use of the syntactic categories that are difficult for them.

APPROACH The current approach draws heavily upon the recently developed techniques for single-subject experimental designs, as described in particular in [5]. Such designs are especially well suited to investigations of communicative deficits, as they provide scientific rigor by allowing each subject to act as his or her own control.

Figure 1 shows the results of one such study, employing a multiple baseline design to explore the efficacy of training on user acquisition of C-VIC prepositions receptively. Inspection of the results demonstrate that: (1) C-VIC preposition use is not functional prior to training; (2) when training is initiated, use of the trained prepositions quickly rises to high levels of accuracy; and (3) functional levels of performance are maintained with no trend towards degradation after training is terminated. Results of this sort help researchers identify the strengths and weaknesses of subject performance in the C-VIC system, and provide tools for conducting more detailed follow-up studies of suggestive phonemena. Specific types of designs which are available to the investigators include—in addition to multiple-baseline designs—withdrawal designs, reversal designs, and alternating treatment designs, among others.

Using such study designs, it is possible to investigate in great detail the effects of manipulations in the communications interface on patients' performance. We have extensively trained patients in the use of the C-VIC alternative communication system and have found that even a severely globally aphasic patient can master the use of simple prepositions in this system, even though prepositions are especially difficult for aphasic patients to use correctly in English. This finding has great theoretical and practical significance because it suggests that such patients can utilize a simple generative syntax and thus make use of communicative power inherent in such an approach. All of the patients we have treated have been able to master the use of a simple hierarchical storage and retrieval system for common nouns. This finding allows the construction of relatively large databases for these patients with relatively transparent search routines to allow them to access vocabulary. Patients may learn concrete representations of verbs slightly faster than abstract ones, but do not generalize them to new situations well. Thus, more advanced graphic features, such as animation, may be necessary for patients to use verbs well.

STATUS The current C-VIC interface, Version 1.0, will soon be supplanted with the more advanced Version 2.0. The expanded features of this system will be used to further investigate the above issues. Specific items to be investigated include: the influence of animation on verb comprehension and use, the depth of hierarchical organization which patients can master usefully, and the degree to which heuristic routines (Artificial Intelligence) imbedded in the program structure and database can aid patients in utilizing syntactic rules.

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SUPPORT

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Design and Operational Features of Portable Blind Reading Aids: Project Overview

PROBLEM There are perhaps 1.5 million visually impaired persons in the US, including around 200,000 veterans; of these, 500,000 persons (including 50,000 veterans) are totally blind [1]. Such visually impaired individuals need more effective and convenient ways of independently handling printed material, both in their jobs and their personal lives.

Interviews of blind persons reveal that current methods of handling such materials all have drawbacks, which are sometimes quite significant. Brailled materials provide perhaps the best-known approach, but they are expensive to produce, bulky to store, and accessible to only 10% of blind persons. Audio tapes are suitable for some types of materials, but they take time to make (which can be a scarce commodity in business), and they can be difficult to review for previously encountered material. Sighted readers sometimes provide a solution, but they are often difficult to locate and schedule, can be expensive, and their use involves a loss of privacy.

In the past decade, the first technologically based reading aids have appeared. The surveys discussed in this report are designed to determine how well these current devices meet reading needs, what capabilities are still needed, and what new technologies can be utilized to meet those needs.

BACKGROUND Two technologically based reading aids have been widely marketed over the past decade, each with some qualified success. The first device is the Optacon, a portable, battery-powered device that provides a tactile display of printed symbols on a 6x24 matrix of vibrating pins. Interviews indicate that—for some blind individuals—it does provide effective access to print material. However, most interviewees find its use quite slow, and typically employ it primarily to identify materials for later, faster processing in some other way. The second device is the Kurzweil Reading Machine (KRM), which scans printed material automatically and provides synthesized voice output of the text. Blind interviewees indicate that non-portability (it is the size of a floor-standing copying machine) and price (around $19,000) are the biggest obstacles to acquisition. Most appreciate its operational characteristics.

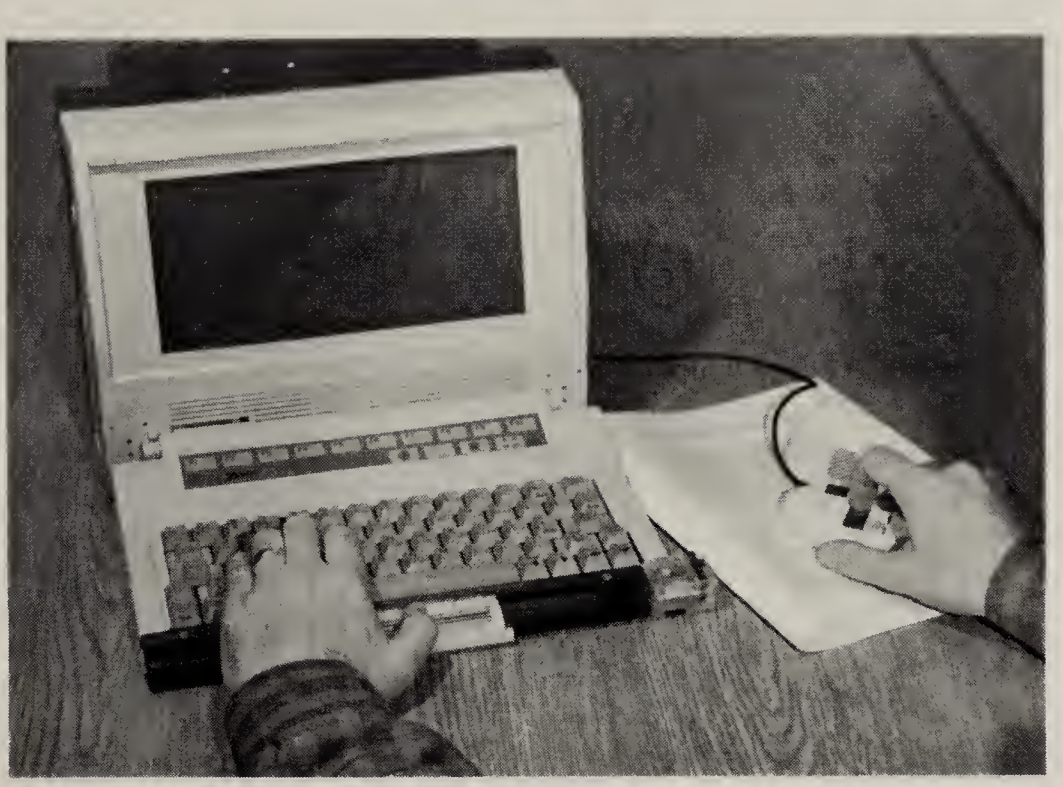

Figure 1. Blind reader/workstation in mock-up.

SIGNIFICANCE The development of a convenient, powerful, and affordable reading aid for visually impaired persons will lead to greater personal satisfaction, an improved quality of life, and greater job competitiveness for the individuals themselves. For rehabilitation professionals, it will enlarge the arsenal of tools available for use in blind rehabilitation and will improve outcomes of the rehabilitation process in appropriate cases. For the Veterans Administration, it will lead to greater cost effectiveness in blind rehabilitation by lowering, in appropriate cases, the unit cost of reading aids which acquired for veterans' use on the job.

1. Western Blind Rehabilitation Center

HYPOTHESIS Commercial computers and associated technology are emerging to help solve these problems. Opportunities exist to devise a portable, battery-powered computer which can recognize text captured by an attached hand-scanned camera. In home or office, it can connect to peripherals to automate text capture. Computer software allows for text entry, storage, retrieval, display, review, editing, and telecommunication.

The central components in this system are: (1) the portable personal computer, capable of operating independently using battery power; (2) a hand-scanned camera and associated hardware and software, which allow computer-recognized printed text to be inserted into the computer; (3) intelligent editing and review software, designed for use by blind individuals; and (4) a speech synthesizer to provide voice output of text on command.

Other components in the approach may be an automatic scanner, which can handle multiple pages at a time, and special peripherals to help blind users navigate easily about text. Such components are either on the market already or are being developed commercially or in-house. Taken together, the package will provide powerful capabilities, at reasonable cost, for use on the job or at home.

APPROACH Our approach has been four-pronged. First, we have been conducting *nationwide surveys of blind individuals* in order to determine the nature and extent of unmet reading needs at present and to establish useful technological approaches to solving existing problems (see Report 63). Second, we have been conducting *human performance studies* on simulations of assistive devices in order to identify crucial design and operational features of such aids (see Report 64). Third, we have been conducting an ongoing *survey of emerging technology* in order to identify commercially available products that are candidates for incorporation into such an aid. And fourth, we have initiated *discussions with manufacturers* for the purpose of enlisting support of various types for furthering this work.

STATUS Two user questionnaires have been compiled and administered. The first is aimed at the blind population broadly, uses multiple choice questions, and is constructed for analysis by statistical methods. The second is aimed at blind individuals who are technologically experienced, as evidenced by at least one year's use of the Optacon, KRM, adapted computer, or the like. It contains open-ended questions and requires content analysis of responses. Preliminary results were published in 1987, and fuller results are slated for publication in 1988.

The simulation system for human performance testing has been assembled, and a comprehensive series of tests have been completed. Construction of the simulation system has generated important components for incorporation into the final assistive device, and the results of the testing, reported in overview during 1987, have allowed suitable design and operational features for the final device to be identified. Technology surveys and discussions with manufacturers have enabled us to identify several key components for incorporation into the final device, and—in one instance—to obtain a unit on loan at no cost for adaptation and development work. A proposal has been submitted to Rehabilitation R&D Merit Review to support the construction and field-testing of this projected reader/workstation.

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Design and Operational Features of Portable Blind Reading Aids: Information from Visually Impaired Users

PROBLEM At the present time, several reading aids exist that enable totally blind individuals to read printed material with a certain degree of success. However, these devices are limited in their capabilities and can be very expensive. The next generation of reading aids will be able to overcome these problems by making use of recent improvements in optical character recognition technology and in the capability and affordability of personal computers.

In order to ensure that these new reading aids best meet the needs of blind users, it is important to interview potential users to find out: What types of documents are most important to be able to read? What special features are desirable? How inexpensive and simple to operate must a machine be to be attractive? What are the limitations of existing machines?

SIGNIFICANCE Information contributed by two telephone surveys reveals a number of important considerations in the design of a reading aid for visually impaired persons. The results of the interview verify the value of obtaining information directly from those for whom the equipment is to be designed.

BACKGROUND Respondents of this survey had used two existing reading aids. The Kurzweil Reading Machine (KRM) is a $19,800, non-portable machine that scans printed material automatically and provides synthesized voice output. The Optacon is a less expensive, portable device that provides a tactile display of printed symbols on a 6x24 matrix of vibrating pins. Neither is completely successful in reading the full variety of print commonly encountered.

HYPOTHESIS Direct interviews of potential users of a technological reading device can provide useful information aiding design and indicating obstacles that must be addressed for successful usage of the device.

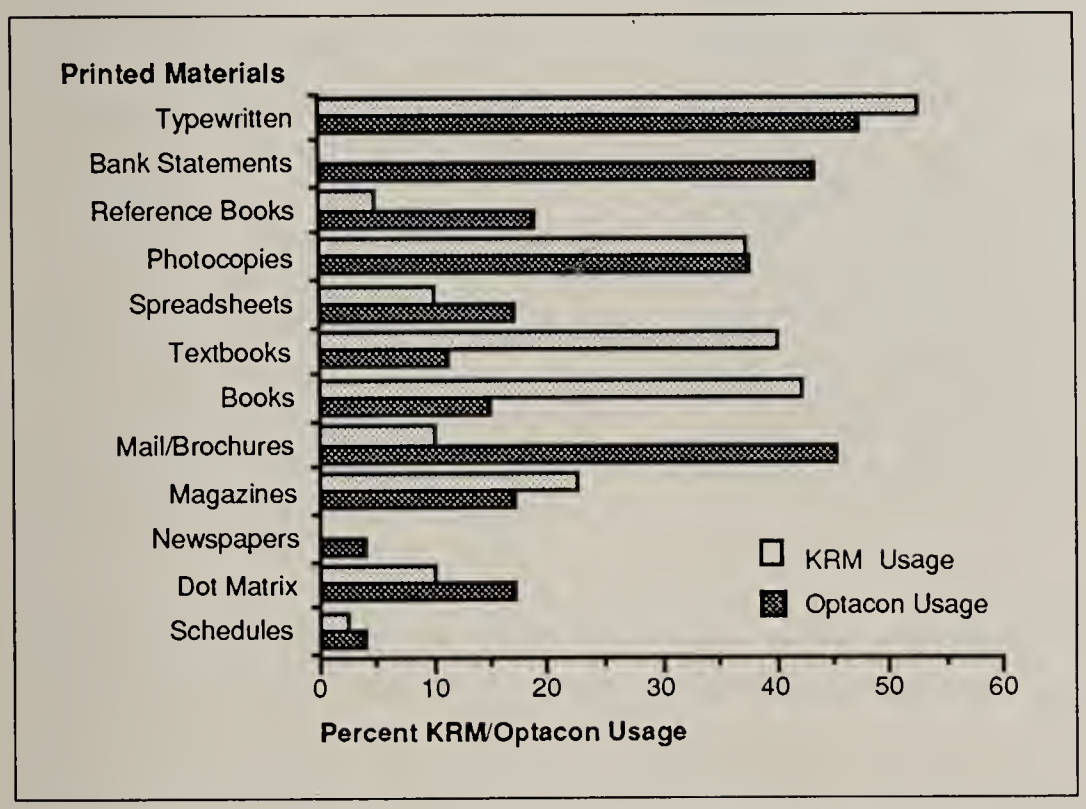

Figure 1. Use of the KRM and Optacon to read different types of printed materials during normal activities. Printed materials are ranked from top to bottom according to the importance rating of those surveyed.

APPROACH 155 visually impaired individuals were interviewed by telephone in the first survey. An attempt was made to reach individuals with differing backgrounds from a variety of sources. Participants were located through the Veterans Administration Blind Rehabilitation Centers, private and public agencies serving the blind, and disabled student services.

The questionnaire contained 43 items, with categorical answers, which obtained descriptive information about the participants' backgrounds, needs for information processing, methods of reading, priority types of print items to be read, current uses of reading-aid technology, ratings of features for a proposed reading aid, cost factors, and training factors. The questionnaire could be completed in approximately 30 minutes.

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At the conclusion of the first interview, 74 experienced users of technology (selected on the basis of at least one year total experience with technological reading aids and/or adapted computers) were asked if they were willing to participate in a future survey examining more closely aspects of technology for the visually impaired. 25 were chosen at random for a second in-depth interview.

The expert user survey consisted of several branching components. Open-ended questions for content analysis were included as well as the previous type of questions with itemized answers. The use of open-ended questions allowed the interviewer to clarify answers during the interview.

This survey examined both the positive and negative features of the participants' experience with technology, and indicated preferences for a broader range of features that a reading aid might contain. Interviews for the second survey increased in time to as much as three hours, completed in one or more sessions on the telephone at the convenience of the interviewee.

STATUS Data collected from the initial survey has been analyzed to provide a description of the population interviewed, patterns of reading, problems encountered in reading, current use of technology, and user-preferred characteristics of a reading machine [1]. A second survey, focused on the experience of users of technology from the first group, is underway, with an analysis of data to be completed.

A significant proportion (53%) of those surveyed have more than one year of experience using technological reading aids and adapted computers for the visually impaired. Almost all (90%) have had some exposure to technology. The most common reading aids in use are the Optacon and the Kurzweil Reading Machine. A very few use optical character recognition (OCR) type devices with computers. While this equipment is commercially available, adaptation for use by the visually impaired is just beginning.

30 of 53 Optacon users with one month or more experience reported using the device to read at least one print category. 27 of 40 KRM users report using the equipment to read print information. Figure 1 shows the types of print read using the KRM or Optacon.

The potential users surveyed indicated a notable preferences regarding weight and cost. A majority of 69% would consider a maximum of 20 pounds transportable, although not necessarily easily portable. Portability is considered important by most of those surveyed. The equipment cost respondents would be willing or able to pay ranged from none (12%) to $15,000 (one subject). Sixty percent stated $2000 or less.

Results of the first survey demonstrated a correlation between the use of technology and employment of visually impaired individuals. These results have led to a spin-off study to examine the nature of this correlation, which could support the training and use of technology in the rehabilitation process of visually impaired individuals.

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Design and Operational Features of Portable Blind Reading Aids: Simulation Studies

PROBLEM By making use of recent advances in microcomputer technology, we can make the next generation of reading aids for blind and low-vision people much more versatile and easy to use than the reading aids that now exist. Among other things, this will involve (1) incorporating features such as processed auditory or tactile feedback to help the user guide a camera over pages of text, and (2) designing and building new control components to help the user retrieve, review, modify, and store text of interest to him. The purpose of this project is to evaluate potential reading-aid features by carrying out human performance studies using prototypes that simulate those features.

SIGNIFICANCE A portable, easy-to-use reading aid will benefit visually impaired persons in a number of ways. It will speed up their rehabilitation by being easier to learn than existing reading aids. It will allow them to compete more successfully in the job market. It will also improve their quality of life by making it easier for them to perform daily activities that involve reading, either for transacting personal business or for pleasure.

The simulation systems provides important leverage to researchers working to develop the reading aid. It is an efficient tool for conducting the necessary background research, since it enables researchers to compare proposed design alternatives quickly and inexpensively in human performance tests.

Figure 1. Macintosh simulation and tracking system.

BACKGROUND Moyers' evaluation of the HS-1 "talking Optacon" showed that a blind reading aid must be easy to operate, or else it will not be used [2]. The HS-1, built in seven prototypes, was the first hand-scanned, voice output reading aid. It used five microcomputers attached to an Optacon to provide automatic character recognition and synthesized voice output of text. During evaluations, blind trainees supported the general idea, but found the actual device too difficult to operate. The major problem was that the user had to manually scan the camera over each line of text very precisely in order for the machine to be able to recognize the characters. Moving the camera either too high or two low produced voice output gibberish. Few trainees were ever able to scan sufficiently accurately, and these lost the ability when they became fatigued after scanning for a time. The evaluators concluded that while hand scanning is handy and desirable, it is only useful if: (1) it does not require too much concentration, and (2) it can be supplemented by automatic scanning for longer tasks.

HYPOTHESIS This project had three hypotheses: (1) that new technology will contribute significantly to producing a new, portable, and easy-to-use reading aid; (2) that targeted studies will show how new technology is to be used in the device; and (3) that a simulation system will provide the necessary tool to conduct the studies. Proving the first hypothesis requires that new and impor-

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tant candidate technologies for the device be identified; proving the second requires that the relevant studies (human performance tests, attitude questionnaire) distinguish between better and worse applications of the technologies; and proving the third requires that the researchers use the simulation system to acquire interpretable and useful answers in the studies conducted.

APPROACH Surveys of emergent technology were used to identify promising components for the new reading aid. We found several candidates, including: (1) a hand-scan camera that captures text, recognizes characters, and inserts them into computers; (2) a portable computer around which to build the aid; and (3) a high-quality speech synthesizer that can be incorporated into the computer. Our targeted studies reflected this component choice.

The investigations focused first of all on the question of tracking accuracy, which was the major problem with the HS-1. We wanted to see how accuracy is affected by different types of feedback—*i.e.*, tactile, audio, visual, and combinations of these. Our simulation system employed a Macintosh computer with a mouse and tone generator, an Optacon driven by a microprocessor under Macintosh control, a DECTalk speech synthesizer attached to the Macintosh, and special hardware and software for overall simulation system control (see Figure 1).

In the simulation, the person moved the mouse back and forth across the table as if he were scanning a document. The position of the mouse was displayed on the screen as a rectangular cursor overlayed on a paragraph of text. The task was to scan each line of text, keeping the cursor centered horizontally over the line being scanned. Feedback was provided in various ways and in different combinations. Audio feedback was a toneless hiss when the cursor was on track, and high or low tones when the cursor strayed too far up or down. Tactile feedback was delivered via the Optacon to the forefinger, and assumed various shapes—a line, a dot, a "rubber-band" line, letters of the text—moving up and down to follow the cursor. Direct visual feedback was provided by looking at the screen of the Macintosh. The software recorded performance during the testing, and provided statistical analyses and graphical presentation of performance following each trial.

STATUS Twenty-two subjects were tested, using simulations of different reading aids. Twelve of these were visually impaired, while ten had normal vision. The results were instructive. As we had predicted, visual feedback provided both the lowest scan times and the highest accuracies in tracking. However, audio feedback came in a rather close second, with scan times averaging roughly twice that of visual feedback, and average errors not significantly greater than in the visual mode. Differences between sighted and visually impaired subjects were insignificant in the audio mode. Tactile feedback came in third, regardless of display shape, and had 50% longer scan times than audio feedback for the best users, while consistently generating greater average errors. Again, there was no significant difference between sighted and visually impaired users using this feedback modality. The results of these tests suggest that some form of audio feedback is appropriate for incorporation into the final device.

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Development of a Low-Vision Training Manual

PROBLEM The severely visually impaired individual is faced with the need to adapt to a distorted visual system created by his or her pathology, to low vision aids and to the changes these create in his or her lifestyle. Clinical experience has shown that visually impaired individuals can learn to use their vision more constructively if appropriate low vision aids are prescribed. Experience has shown, however, that simply prescribing low vision aids is often not sufficient to restore the individual's visual functioning. Research over the past 10-15 years indicates that perceptual training can provide improvement in visual function. The problem is to develop a systematic perceptual training program which can be applied in existing clinical settings.

SIGNIFICANCE The causes of severe visual impairment are largely age related. The 1984 Health Survey Supplement conducted by the National Center for Health Statistics estimated that over 2 million people over the age of 60 are severely visually impaired. Since about one out of eight Americans is a veteran, this data would estimate that some 250,000 veterans are severely visually impaired. This number far surpasses the current abilities of the Veterans Administration to provide rehabilitation services. Similarly, the number of non-veteran, severely visually impaired individuals far exceeds the capacities of public and private rehabilitation agencies. A perceptual training program that improved patient visual performance and that could be largely administered as patient homework would be a significant step in meeting the needs of the visually impaired population. It would be cost-effective since it would require only minor changes in existing rehabilitation procedures.

BACKGROUND Since the early 1970s the Western Blind Rehabilitation Center has been engaged in extensive low vision research. This research has helped to establish an exceptional vision rehabilitation program, has determined the efficacy of numerous low vision aids, and has established the critical role played by training in vision rehabilitation. During this time many researchers have made significant contributions to vision rehabilitation. These contributions include the development of new vision testing instruments, new low vision aids, improvements in vision training, and the beginnings of a theoretical basis for vision rehabilitation.

The perceptual research of James and Eleanor Gibson and many others has demonstrated the remarkable properties of the visual system, including its plasticity. This plasticity can be shown by the relative ease with which even the upside-down and backwards text in Figure 1 can be read. In the area of a theoretical basis, Dr. Natalie Barraga [1] has developed an eight stage model of visual development in visually impaired children. The model describes the stages of visual development from the ability to visually fixate an object to the ability to read. This model is very important since it provides a framework on which tests of visual function can be constructed and from which remedial therapies can be developed.

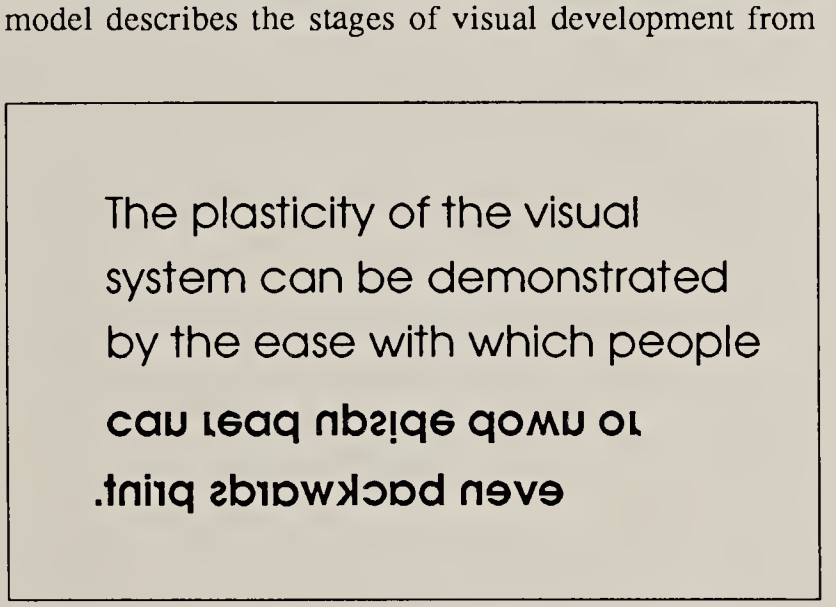
The plasticity of the visual
system can be demonstrated
by the ease with which people
can read upside down text
even backwards print.

Figure 1. Plasticity in the visual system. A person can learn to read text even when words are printed backwards or upside down.

Our early work demonstrated the potential for vision training in improving patient acceptance of low vision aids [2], patient visual performance with low vision aids [3], and visual performance without low vision aids [4]. This work lead to a closer examination of training

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methods and procedures. One outcome of these examinations was the recognition of perceptual tests, such as the Frostig Figure-Ground test, as predictors of reading performance. In brief, this early work demonstrated the plasticity of the visual system of adult, visually impaired individuals, and provided new means of assessing and predicting performance.

Once the links between visual perceptual factors, visual rehabilitation training, and patient performance were established our attention turned to developing systematic training paradigms suitable for use in a wide variety of settings. As this preliminary work progressed, our research data supported the similarity between adventitiously visually impaired adult veterans and the developmental hierarchy defined by Barraga for children. These findings suggested to us that it would be possible to define severity of loss in terms of Barraga's hierarchy; that is, the more severe the loss, the more the patient's visual function regresses along the hierarchy. This would be extremely important since it would suggest specific remedial training techniques.

HYPOTHESIS It is hypothesized that adventitious vision loss in adults follows a reverse pattern to the development of visual perception in children. That is, adults who experience a vision loss will regress along the visual perceptual hierarchy. The more severe the loss, the greater the regression. For example, a mild loss may impair reading abilities, but not figure-ground abilities. Additionally, it is hypothesized that visual perceptual training, using materials specific to each hierarchical stage, will be effective in rehabilitating visual function.

APPROACH Initial work using materials analogous to the six highest levels of Barraga's hierarchy indicated only four were useful for adults. Subsequently we developed and tested a set of training materials that incorporated four stages: target/match, copy/draw, figure-ground, and reading. These materials have been pilot tested and shown to be effective in training improved visual performance. Additionally, a questionnaire has been developed to assess reading patterns. The questionnaire is designed to assess whether our training regimen changes patient reading behavior (that is, if visual function is improved does the patient read more?).

STATUS Current work focuses on the development of additional training materials, particularly for reading training, and the development of a questionnaire for assessing patterns of reading. Future work will expand the available training materials, develop testing materials to assess visual performance, assess the effectiveness of the training and testing materials, and compile the materials into a training manual suitable for use in a variety of clinical settings.

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SUPPORT

Western Blind Rehabilitation Center
RR&D Core Resources

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Computer-Aided Clothing Design for People with Special Needs

PROBLEM Currently the clothing needs of people with physical disabilities and limitations are not adequately addressed by mainstream designers and manufacturers. If garments do exist, the selection is often limited, they can only be purchased through the mail, and they are designed to meet the physical requirements of the average wheelchair user or the average person with arthritis. In addition, as disabilities vary in their cause, stage of development, and effect on the individual's facility with dressing and performing other basic functions, each physical limitation, or combination of limitations, requires a different solution [1].

Evidence suggests that custom-designed garments are ideal for meeting special needs. Traditional methods for producing custom garments, however, are time and labor intensive, and results are expensive, one-time solutions. Fortunately, recent developments in personal computer technology can now put custom clothing within the reach of the disabled population.

SIGNIFICANCE This research is especially significant given the current economics of health care and the forecasted increase in the elderly population. In 1980 there were 27 million people over the age of 65 living in the United States. That number is expected to rise to 39.3 million, or 14% of the total U.S. population, by the year 2010 [2]. These predictions are of major concern because the prevalence of chronic illness will rise in proportion to the number of elderly people. Furthermore, dependency in dressing is one of the strongest predictors of future residency in a nursing home [2].

Those who will directly benefit from this technology include people with disabilities that are characterized by functional limitations in the hand and arm, limited range of motion and limited overall body strength (*i.e.*, arthritis and spinal cord injury). This technology can also be applied to anyone with a unique body shape or a particular fitting problem such as those associated with aging, curvature of the spine, amputation, or the use of a wheelchair.

BACKGROUND Since the project's inception, the development team has worked toward applying flat pattern drafting techniques in a computer-aided design environment. AutoCad® (AutoDesk) and Synthesis™ (TransformerCAD) have been selected as our software tools. AutoCad® is a microcomputer-based computer-aided design package. Synthesis™, which works in conjunction with AutoCad®, allows a designer to change master drawings via information stored on a spreadsheet.

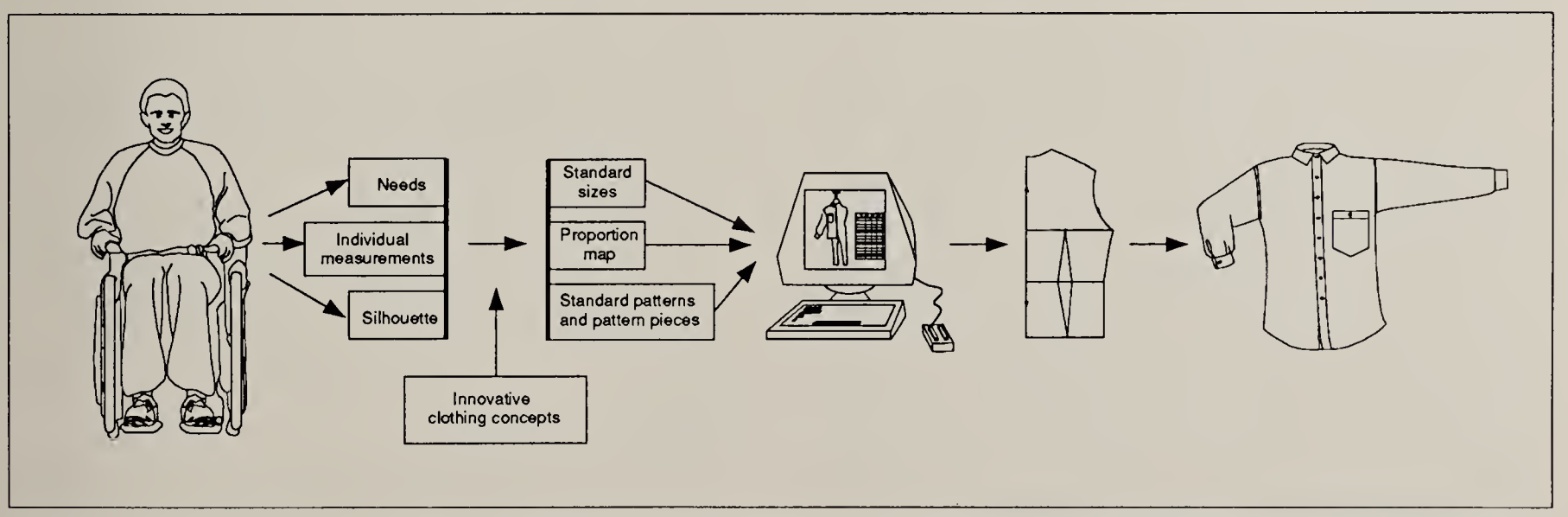

Figure 1. Individual needs, clothing preferences, and capabilities must be considered in addition to body dimensions and silhouette when developing a custom pattern. Once this information is known, a standard pattern, or selected pieces from several patterns, can easily be modified.

Some investigation into three-dimensional modeling of musculoskeletal anatomy occurred as part of the initial development effort. For example, we designed a 3D wireframe human model that can be scaled about different axes to create a variety of body types. The model has link-end pivots that permit rotation in user-defined planes and ranges of motion.

In the Fall of 1986, the RR&D Center sponsored a student design project in human factors and design in the Mechanical Engineering Department at Stanford University. For this project the students were required to design a fastener that would enable an individual with decreased manipulation capabilities and limited range of motion in the upper torso to dress independently. Solutions ranged from the futuristic (a zipper-like magnetic strip fastener) to the fundamental (adapted off-the-shelf fasteners). Some solutions were especially innovative in that they applied technology used by industries other than the textile and apparel industries.

HYPOTHESIS We believe that clothing which compensates for functional limitations and encourages people to dress themselves can reduce the need for institutional care and contribute significantly to the quality of life of disabled individuals.

APPROACH The intent of this project is to demonstrate that CAD technology can be used to design well-fitting clothing that is appropriate to the needs of people with disabilities. The specific goals are: (1) to collect sufficient human factors and anthropometric information (such as height, weight, body girths and lengths) to set up a simple database; (2) to create a link between that database and the CAD environment; and (3) to test this system by producing patterns and clothing samples for several different sets of anthropometric data.

Our focus is on overall system development and the generation of accurate digital and graphic representations of the human body for use in garment design and construction. More specifically, basic flat patterns and two-dimensional images are being created from standards currently used by the home sewing industry. Anthropometric information will be gathered as part of a study to develop garments for use in patient rehabilitation. We are also investigating different ways of taking human body measurements. It will be important to determine the quantity, as well as the quality, of measurements that are necessary to produce a custom fit.

Once sufficient data is acquired for an individual, a flat pattern can be drafted and a test garment constructed. Appropriate changes will be made to the pattern, as necessary, to achieve a fit.

STATUS Current efforts are on developing garments for use in patient rehabilitation. Researchers are collaborating with occupational therapists and doctors in the spinal cord injury and rehabilitation medicine clinics at the Palo Alto VA Medical Center. The hope is to quantify some of the work that has already been done in the clinics while investigating new concepts in custom clothing design.

We are currently developing specifications, such as fabric requirements and sewing instructions, for altering ready to wear garments. We are also drafting a pattern for a halo shirt to be worn by newly injured spinal cord patients that require neck stabilization. Once it is on the computer system, the basic halo pattern can be easily customized for individual patients.

Future projects include a clothing needs survey and a "visual" questionnaire and capability profile for ADL (activities of daily living) evaluation. Both of these applications will be developed using HyperCard™, a graphic and textual information organizer for the Macintosh™ computer.

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SUPPORT

RR&D Core Resources

Eric E. Sabelman, PhD
Conal B. Wilmot, MD[1]

Devices for Support and Transportation of Acute Spinal Injury Patients

PROBLEM Individuals who injure their cervical spines are exposed to risk of further injury by unintentional spinal motion during transport by helicopter to a specialized spinal center and during routine nursing and therapy in the hospital. There is a need for an improved means of immobilizing the unstable spine and applying traction to realign the damaged vertebrae. Equipment designed to meet this need must be objectively compared to existing devices under both laboratory and clinical conditions.

SIGNIFICANCE There is a body of evidence that suggests that at least part of the neurological deficit accompanying spinal injury is due to factors other than the initial trauma, such as continuing compression of the spinal cord by displaced vertebrae and progressive edema [1]. It is imperative to begin fracture reduction as early as possible after injury and to maintain it uninterrupted during transport. Thus, residual paralysis which must be compensated for by later rehabilitation might be substantially reduced.

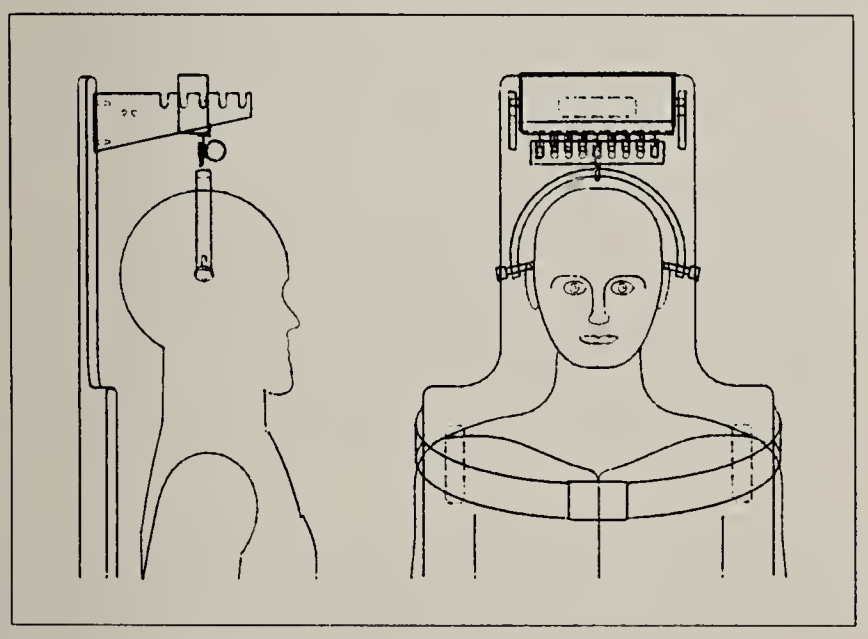

Figure 1. Backboard/traction unit.

BACKGROUND Although equipment for moving patients in traction exists [2,3], it is often inaccurate, sensitive to acceleration and poorly adapted to newer helicopters [4].

After a study conducted by NASA-Ames Research Center demonstrated inconstancy of traction during ground and air transport [5], Wilmot and colleagues approached the RR&D Center regarding need for improved apparatus. A prototype laminated-wood backboard with constant-force traction was delivered for trial in 1980 [6]. A second design was developed in 1982 using criteria concentrating on aesthetics and manufacturing [7].

HYPOTHESIS Our design philosophy is based on the application of advanced materials, knowledge of the biomechanics of the injured spine, and intensive interaction with emergency medicine and acute rehabilitation physicians, nurses, and therapists. It is hypothesized that this synergistic approach will yield significant improvements in patient welfare.

APPROACH Equipment must be compatible with helicopter and ground transport vehicles, and with CT (computerized tomography) and MRI (magnetic resonance imaging) diagnosis. Dimensions and materials are therefore critical; non-magnetic X-ray translucent carbon-fiber/epoxy composites are used extensively. Experimental head and neck restraints use thermoformable materials which can be custom-fitted to an individual patient.

The current series of transport backboards are made of carbon-fiber/epoxy skins over a curved foam core. The modular traction device has nine sets of constant-force springs generating a nominal 2.8 lbf each on 18-inch output cables, which are attached as needed to a summing bar (Figure 1). A pre-production design having a single spool for each output with extension limited to 6 inches should yield a smoother output at less cost.

Laboratory testing of prototype and commercial backboards consists of measurement of deflection under end-supported center-loaded bending up to 200 lb. A model of the traumatized cervical spine suggests that as little as 2.4 degrees slope may produce an additional 5% occlusion of the spinal canal. Of 8 devices tested, one that is in commercial production was marginal by this standard (Figure 2); others have limitations such as poor

1. *Santa Clara Valley Medical Center*

X-ray compatibility, excess weight or high cost.

STATUS Data are being gathered and analyzed on clinical usage of third-generation backboard/traction devices. Other activities include design iteration of lateral head restraints, x-ray compatible skeletal fixation tongs and halos, and pre-production versions of the traction device.

Backboard/traction systems have been in clinical use by Santa Clara Valley Medical Center and by the Life-Flight helicopter group at Stanford University since February, 1985, with no adverse effects. The Stanford/Life-Flight team continues to fly patients using the backboard/traction system, and has submitted papers to the University Association for Emergency Medicine and ASHBEAMS.

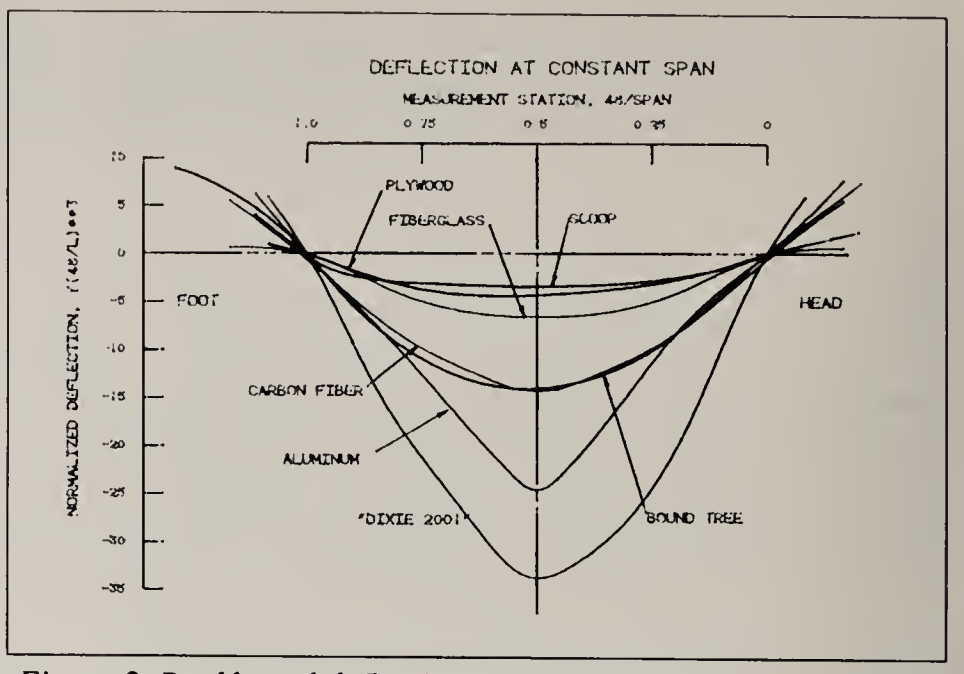

Figure 2. Backboard deflection at constant spin

One backboard/traction system was sent to another spinal cord injury center as part of a multicenter clinical trial. This experience emphasizes the need for adequate familiarization of physicians and nurses with the equipment, high-quality instructional videotapes, on-site maintenance, and provision of at least two backboard/traction units, one for field use and one for in-hospital use.

Current and future activities that have grown out of the design study include: (1) Continued efforts to transfer the technology into the commercial sector, and potential collaboration with private industry as mandated by the Technology Transfer Act of 1986. Collaborative research may include head restraints, spinal alignment monitoring, actively servocontrolled cushions, and improvements to kinetic beds. (2) Feasibility studies of semi-invasive methods of preserving spinal cord viability during the first few hours after injury. It has been hypotheisized that in at least some cases, permanent damage occurs due to post-traumatic swelling and vascular stasis, and that impaired blood supply to the cord can be supplemented by extracorporeal perfusion of the cerebrospinal fluid.

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SUPPORT

RK Davies Medical Center seed grant (1983)
Paralyzed Veterans of America (1984-85)
RR&D Core Resources

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Accelerometric Body-Motion Detection in Spinal Injury Patients

PROBLEM Motion of the head relative to the lower body is of clinical significance in maintenance of spinal stability during movement of spinal injured patients. Recent advances in acceleration detection and real-time data acquisition technology permit direct measurement of the stimuli (*e.g.*, vibration and impact) which impart such relative motion. These measurements can be integrated to yield body segment displacement. This project endeavors to apply this technology to subjects exposed to the motion environment typically experienced by the acute spinal injury patient.

SIGNIFICANCE Very little is known of the acceleration and vibration environment experienced by acute cervical spinal cord injury (SCI) patients, despite widespread recognition that movement of the head relative to the body could have severe neurological consequences. Common procedures and apparatus for stabilizing the damaged spinal column include immobilization during the earliest stages of primary care, traction while in hospital, and closed reduction, internal fixation, or bone graft surgery for permanent realignment. Until permanent bony repair is effective, the spinal cord is subject to iatrogenic trauma through inevitable movement of the vertebrae despite the best efforts to maintain spinal stability.

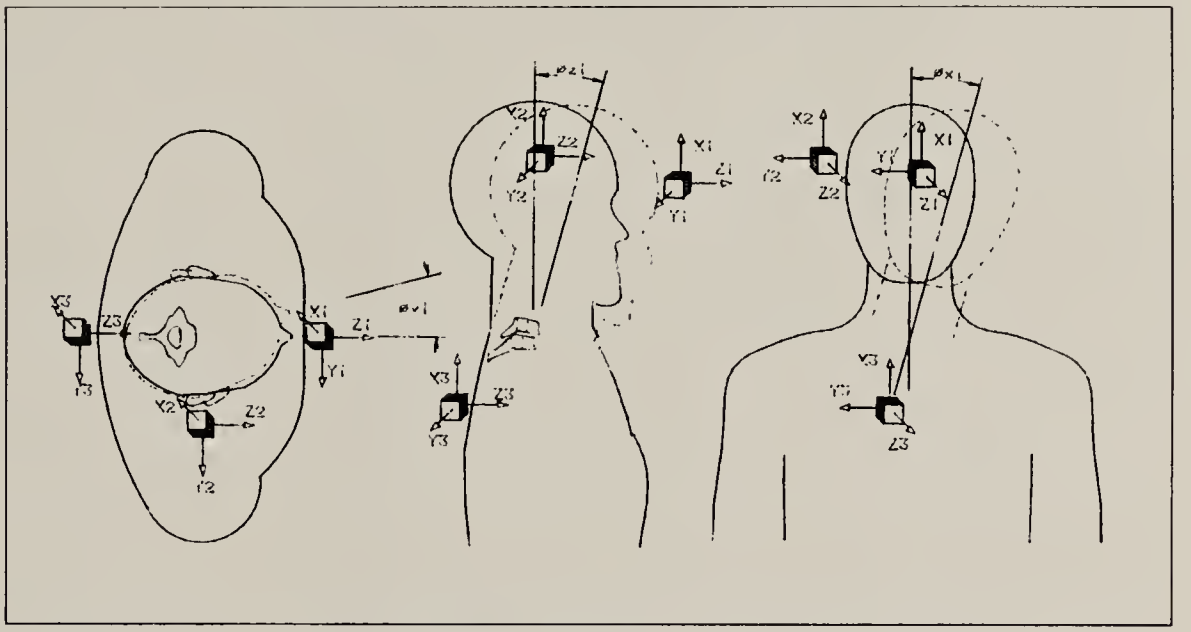

Figure 1. Cervical spine body model.

HYPOTHESIS Our underlying assumption is that externally measured accelerations are indicative of vertebral motion, and reducing vertabral motion is significant to the prevention of further damage to the spinal cord.

APPROACH Because quantitative data on early SCI patient environment is lacking, we propose to assemble and employ a self-contained package of acceleration detection and analysis instruments to examine hitherto unmeasurable biomechanical inputs and body segment responses. Acceleration of the head, body, and patient support (Figure 1), and variations in traction force (if applied) will be digitally recorded and integrated to yield velocity and displacement during a sequence of intra-hospital transfers and procedures experienced by SCI patients (Figure 2).

The proposed study will address these questions: (1) What is the motion environment experienced by the acute SCI patient? (2) How well do current procedures and equipment for patient handling prevent motion of the head relative to the body?

This preliminary study will be restricted to a subset of the total sequence of potentially motion-inducing events, so as to verify the utility of accelerometry as a measurement technique and to test the correspondence of head-to-body motion to measures of patient status such as X-rays, CT scans, and neurological profiles before and after one or more treatment steps.

Specifically, in-hospital aspects of patient handling have been selected as the subset for investigation, since in-patient transfers, lifts, movement for therapy and diagnosis, and nursing on kinetic beds occur in a well-defined setting, are frequently repeated on a single pa-

1. Santa Clara Valley Medical Center 2. Stanford University

tient, and potentially can inflict unnoticed but neurologically significant displacement of the neck. Data from sensors will be reduced to stimulus (patient environment) and response (body segment) accelerations, velocities, and displacements (and traction force, if applicable) as a function of time.

These results will be compared to the intended patient manipulation or movement as recorded on time-synchronized audio or video tape. Where possible, individual patients will be followed through the entire sequence of procedures, and their motion history correlated with pre-admission, in-patient, and discharge X-ray, CT, and neurological status.

STATUS Currently available equipment is limited to four channels (3 acceleration axes and traction force) on an IBM PC/AT microcomputer, using LabTech "Notebook" data acquisition software. Tests have been run on a non-invasive traction backboard known as the "TACIT," under commercial development, and on three types of cervical collars (Philadelphia, "Stifneck" and "Malibu"). Each run consisted of 120 seconds of data collection during which the device was installed on a supine able-bodied volunteer, who was then log-rolled 90 degrees to each side, raised to a sitting position one or more times, and asked to exert muscular effort against the restraint in compression, in flexion/extension, and laterally.

Results of tests on the "TACIT" showed that it could be installed with little (<0.05 g) imposed acceleration and provided adequate immobilization of the head, but that traction force was subject to wide fluctuation due to internal friction. All three cervical collars permitted measurable head movement, and one (the "Malibu") could not be installed without momentary accelerations of about 0.2 g. Future work will include tests designed to confirm the assumption that these measurements can be correlated to skeletal biomechanics.

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SUPPORT

VA RR&D Pilot Study (1988)
RR&D Core Resources

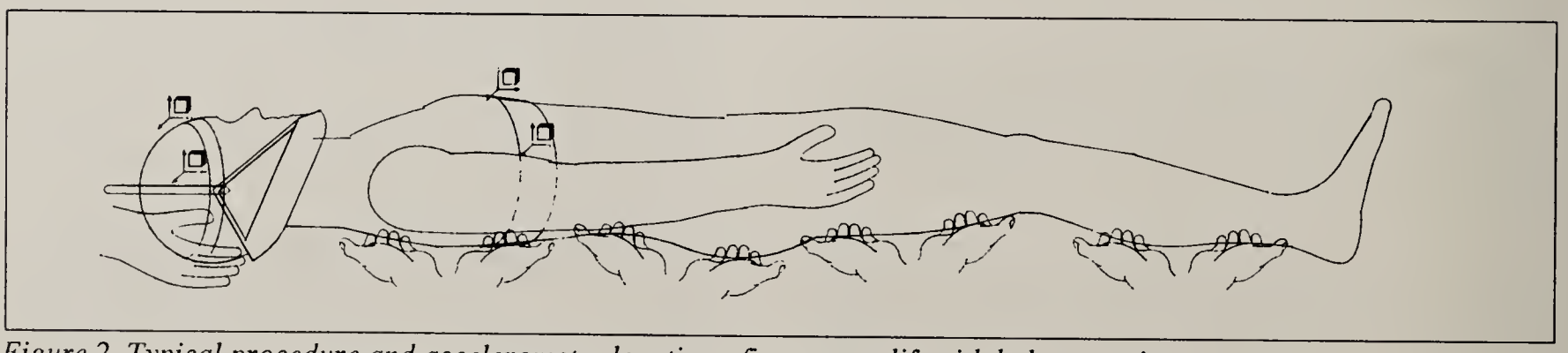

Figure 2. Typical procedure and accelerometer location: five-person lift with halter traction

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Accelerometric Body-Motion Detection in the Fall-Prone Elderly

PROBLEM Recent advances in acceleration measuring and real-time data acquisition technology are being applied to the analysis of upper body instability contributing to or accompanying falls in the elderly. Heretofore, research into the proximate causes of falls has been limited to *post facto* accident reconstruction and probabilistic studies of site-specific falls (*e.g.*, stairs).

We propose to utilize improved instrumentation that will make possible: (1) recording an individual's movements during an interval *preceding* a spontaneous fall irrespective of location; (2) identifying patterns of movement that accompany loss of balance before a fall actually occurs; (3) and ultimately, alerting the individual of pre-fall behavior and, if necessary, signaling a remote attendant that a fall has taken place.

SIGNIFICANCE Falls present a serious health hazard to elderly and partially disabled ambulatory persons. For example, nursing home patients alone account for 1800 fatal falls per year (2 falls/patient-year, 2.4% resulting in hip or other fracture). Examination of spontaneous falls, including patterns of movement that lead to loss of balance, could provide information valuable for analyzing causes of falls and minimizing resultant injury.

The methods developed in the pilot study will permit analysis of falls outside the controlled laboratory environment. Data on spontaneous falls may be useful for: correlating pre-fall motion with known musculoskeletal and sensorimotor deficits; predicting the magnitude of post-fall injuries, based on calculation of energy absorbed during a fall; and investigating the causal relationship of falls and hip fractures.

HYPOTHESIS The underlying basis for the proposed investigation is that falling is a quantifiable act; a fall is a detrimental interaction between one's sensory and motor capacities and the environment. When a person walks, turns, sits, stands, or climbs stairs, his or her body moves through space in characteristic patterns of acceleration and deceleration. A fall is presumed to be a time sequence of movement that is distinctly different from normal activities; the final phase of a fall is an abrupt pitching of the head and upper body relative to the lower body.

APPROACH In this preliminary study, we will apply recent improvements in acceleration sensors and digital recorders during laboratory tests of gait and balance, and during unconfined walking in the normal hospital environment (Figure 1). Quantitative documentation of head and body motion during clinical gait and balance assessment may eliminate possible errors of qualitative judgement.

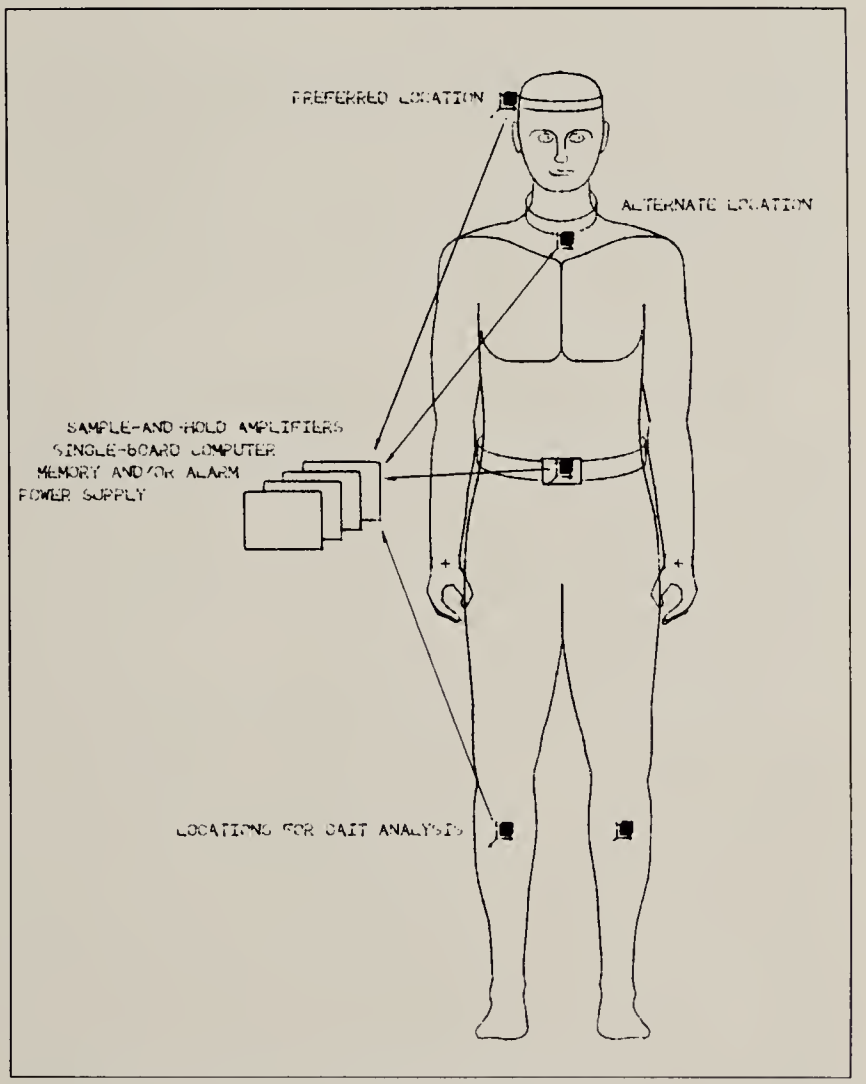

Figure 1. Elements involved in fall detection.

Our ultimate goals are to determine the sequence of events that precipitate a fall, and if the sequence is repeated, to predict and possibly prevent a subsequent fall.

1. Geriatric Research Education and Clinical Center 2. Stanford University

Our apparatus will use the motion signature of the fall itself as a trigger to lock in measurements of pre- and post-fall events, which are otherwise difficult to isolate.

Relative head-to-body acceleration will be measured, first on able-bodied young and old volunteer subjects, and later on elderly patients, as they perform a standard gait and balance evaluation protocol. This series of simple tests of standing, turning, stair-climbing, etc., conventionally includes a three-point qualitative evaluation scale, which will be expanded to reflect the discrimination available through quantitative accelerometry. Acceleration data (plus velocity and displacement derived by integration of acceleration over time) from each subject will be analyzed to distinguish movement patterns common to all persons performing a balance test or other activity from those characteristic of poor postural control, and to identify pre-fall patterns if spontaneous falls occur.

STATUS The Geriatrics Research, Education and Clinical Center (GRECC) of the Palo Alto VA Medical Center has particular interest in factors affecting gait and balance, especially as it relates to Alzheimer's disease. The volunteer pool of the Aging Study Unit is available for the proposed research as a baseline population typical of independently living persons.

The Neuromuscular Biomechanics Division at the Palo Alto VA RR&D Center has previously developed computer simulations of human posture and jumping using a planar model of the human body. This model will aid the proposed study by facilitating interpretation of measured accelerations.

Exploratory experiments with a head-mounted accelerometer are underway, using cables connected to stationary amplifiers and an IBM PC-AT microcomputer containing an IBM DACA analog-to-digital conversion board. Data acquisition and analysis is performed using Labtech NOTEBOOK, which provides real-time graphic display and disc storage for later integration, curve-fitting, and/or Fourier transform spectrum analysis. A typical recording session is 120 seconds long, acquires data at 100 millisecond intervals, and is capable of distinguishing 0.05-g variations imparted by head-turning or jumping.

SUPPORT
RR&D Core Resources

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Skin Deformation and Blood Flow Under External Loading

PROBLEM Spinal cord injury patients are generally more likely to develop pressure sores than are able-bodied individuals because of the loss of mobility and sensation. But within the spinal cord population, some patients are significantly more prone to such problems than others, and the reasons for these differences are not known. Since pressure sores are always preceded by a compromise of blood flow in the skin, this investigation is directed toward the measurement of skin blood flow response to external pressure loading in spinal cord patients.

SIGNIFICANCE If there are indeed differences in skin blood flow response to loading which can be easily measured, then it may be possible to identify those patients who are more susceptible to pressure sores upon admission to the hospital. This would permit a shifting of nursing care in such a manner as to diminish the incidence of pressure sores in VA hospitals. At the present time, the average cost of treatment for pressure sores is about $15,000 per patient per year, not to mention the cost in patient discomfort and loss of time from work or school. A method of identifying patients at risk would be most valuable in diminishing these costs.

BACKGROUND There have been a limited number of studies in which skin blood flow under external loading has been measured by a number of different techniques, all of which have used rather indirect methods. The findings of such investigations have shown that there is generally a decrease in skin blood flow with loading, although there seems to be considerable variation in the quantitative results, and that blood flow in the skin apparently ceases at a local pressure loading of about 100 mm Hg in able-bodied young subjects. These occlusive pressures are evidently much lower in older and in paralyzed subjects. But the large variability of the curves of skin blood flow vs. pressure makes it difficult to draw any meaningful conclusions. The present study differs from previous studies in two major respects: (1) a dimensional analysis is carried out to insure that all of the necessary quantities are measured and are treated in

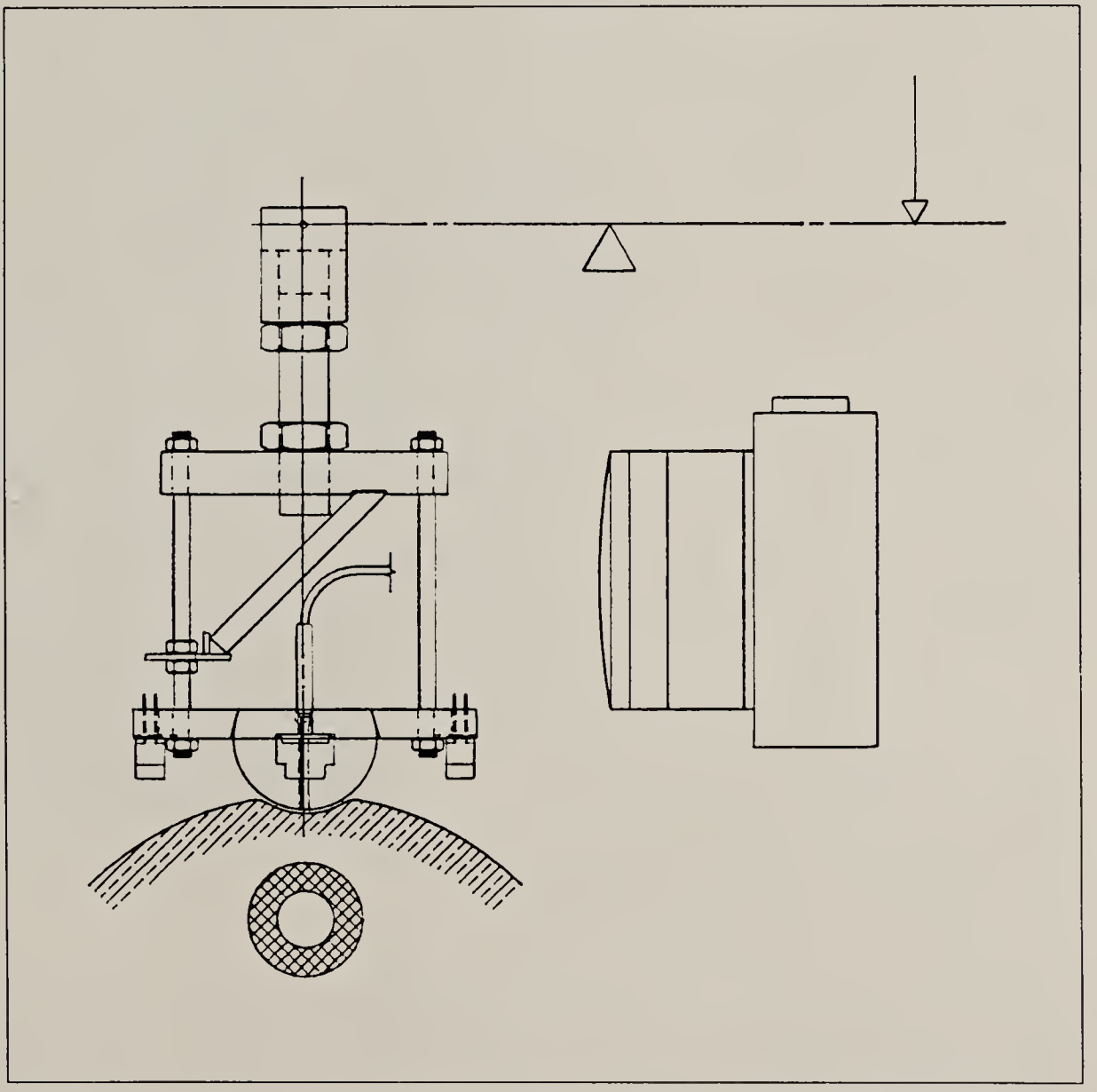

Figure 1. Schematic sketch of indentor assembly showing load application and measurement systems. Note optical fiber for measuring skin blood flow.

1. *Children's Hospital at Stanford*

the appropriate nondimensional forms to give meaningful results; (2) a relatively new noninvasive technique is used for the direct measurement of skin blood flow.

HYPOTHESIS It is hypothesized that the response of skin blood flow to external loading will be found to be significantly different between those patients who do and do not develop pressure sores, provided that all of the necessary quantities are accurately measured and that the results are plotted in the appropriate nondimensional forms.

APPROACH We use cylindrical or spherical indentors combined with a laser doppler flow meter (LD 5000, MedPacific, Seattle) to measure skin blood flow response to loading in able-bodied subjects and in spinal cord patients who do and do not have a continuing problem with pressure sores. Dimensional analysis has shown that percentage reduction of skin blood flow due to loading depends upon only two dimensionless variables: (1) the ratio of skin indentation to bone depth, and (2) the ratio of indentor size to bone diameter. Measurement of pressure is not necessary, and the required measurements can be made over any bony prominence, since these results are not specific to any one site. The essential measurements are bone depth, skin indentation, and skin blood flow. These measurements are combined to produce the necessary dimensionless plots of percent blood flow reduction versus percent tissue compression.

STATUS Our earlier studies showed that the laser doppler flowmeter does not accurately measure skin blood flow under conditions of high loadings, since instrument errors become increasingly significant as blood flow is reduced by loading. Therefore, a new apparatus has been designed to apply only small displacements of the skin while making accurate simultaneous measurements of skin displacement and skin blood flow.

Skin indentation relative to the surrounding skin surface is measured by means of four photodetectors mounted into the indentor support mechanism. Skin blood flow is simultaneously measured on a continuous basis using the laser doppler flowmeter (see Figure 1). In order to check this technique against traditional methods, we also intend to measure contact pressure by determining applied loads and the area of contact using photographic methods with a fluid interface. Bone depth is measured with a portable echo doppler unit (Toshiba Sonolayer SAL-30A with ultrasonic phased array probe).

The photodetectors have been breadboarded, tested, and calibrated so that we are operating in a linear range of output with small displacements. The supporting mount and the spherical indentors have been machined and fabricated, and the entire system is now ready for initial testing on human subjects.

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SUPPORT

VA RR&D Pilot Study (1987-present)
RR&D Core Resources

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Alterations of Blood Rheology in Spinal Injury Patients

PROBLEM The development of pressure sores is preceded by a shutting off of blood flow in the small vessels of the skin. Since blood flow in these vessels is strongly influenced by blood viscosity, red-cell rigidity, and red-cell aggregation, it is planned to study blood rheology (*i.e.*, flow and/or deformation characteristics of blood and its components) in spinal cord injured patients.

SIGNIFICANCE Spinal cord injured patients are subjected to the risk of pressure sores because of prolonged bed rest or wheelchair confinement combined with the loss of mobility and sensation. If altered blood rheology contributes to the risk by impairing circulation in the skin, then some type of blood testing might be usable as a technique for identifying hospital patients at admission who will need additional preventive care. In addition, a role for red-cell rigidity or aggregation in the tendency toward pressure sores would suggest the possibility of a degree of prevention by using selected drugs which can alter these properties.

Figure 1. Rheoscope for measuring and observing red cell aggregation.

BACKGROUND Increases in red-cell rigidity, red-cell aggregation, and blood viscosity have been reported in diabetes, in certain cancers, and in other diseases involving the small blood vessels. It has also been shown that the red cell recovers its flexibility very quickly after prolonged application of external pressure to the skin of able-bodied subjects, but red-cell rigidity has never been studied in spinal cord injured subjects. The high incidence of pressure sores and venous thrombosis in acute-spinal cord injured patients indicates that red cell behavior may indeed be altered by spinal cord injury. Therefore, we plan to study blood rheology in spinal cord injured subjects with and without pressure sore problems and to compare those results with comparable measurements in blood samples from the able-bodied population.

Red-cell aggregation can be observed and measured under controlled conditions by the use of a rheoscope, an instrument combining a transparent cone-plate viscometer with an inverted microscope (see Figure 1). This instrument permits illumination, observation and photography of red cell aggregates in motion at controlled rates of shear corresponding to conditions in the vessels of the microcirculation. A separate instrument, a metal cone-plate viscometer, is used for accurate measurement of blood viscosity. Special filters are used to determine red-cell rigidity by measuring filtration pressures at controlled flow rates with pore sizes smaller than a single red cell.

HYPOTHESIS It is hypothesized that spinal cord injury may produce a change in the rigidity and aggregation of red blood cells, thereby increasing blood viscosity and aggregation and inhibiting blood flow in the microcirculation. If this is the case, it is expected that the tendency to develop pressure sores would be increased because less external pressure would be required to cut off blood flow, and recovery of blood flow would be impaired.

APPROACH It is planned to draw blood from able-bodied subjects and from spinal cord injured patients with and without pressure sore problems. We will measure the following characteristics:

(1) whole blood viscosity,
(2) red cell aggregation,
(3) red cell deformability,
(4) plasma viscosity,
(5) sedimentation rate,
(6) complete blood count and platelet counts, hematocrit and red cell indices,
(7) plasma fibrinogen levels.

Items 1 through 5 will be measured using a Brookfield microviscometer and a Wells-Brookfield rheoscope as well as filtration techniques. Items 6 and 7 are periodically performed by Laboratory Services on every patient in the Medical Center on a routine basis. It is expected that any significant rheologic differences will be detected by these measurements if they exist.

STATUS A small laboratory space has been set up within the Spinal Cord Injury Center for the study of blood rheology. At the present time, the viscometer, rheoscope, water bath, and other auxiliary equipment are being set up and readied for rheologic measurements.

SUPPORT
VA RR&D Pilot Study (1988)
RR&D Core Resources

Alvin H. Sacks, PhD
Inder Perkash, MD

The Bent-Finger Technique for Studying Skin Biomechanics Related to Pressure Sores

PROBLEM The response of skin blood flow to external pressure loading is believed to be related to the tendency to develop pressure sores. The study of this response ordinarily involves the use of rather sophisticated instrumentation for the measurement of blood flow. A much simpler technique is explored here which involves the whitening of the knuckle in a bent finger.

SIGNIFICANCE Because of a loss of mobility and sensation, spinal cord injured patients are clearly at risk for developing pressure sores when confined to beds or wheelchairs. But not all such patients actually do develop such sores. Since pressure sores are slow and difficult to heal, often requiring surgery, and since there are not enough nurses to turn or move each patient frequently enough to prevent pressure sores, it would be most useful if we could identify upon admission to the hospital those patients who are most likely to develop pressure sores, especially if we could do this using a simple measurement of skin blood flow under loading.

Figure 1. Fixture and probe for ultrasound pictures in water bath.

BACKGROUND A dominant precursor of pressure sores is the prolonged shutting off of capillary blood flow. It is this same shutoff of skin blood flow that produces a white knuckle when a finger is bent beyond a certain angle. Furthermore, there is a clear analogy of the skin over the bent knuckle with the classical engineering problem of the belt in tension over a pulley.

This latter observation provides us with mathematical equations which show that the dimensionless ratio of pressure to elastic modulus (of the skin) is equal to the product of the dimensionless skin elongation and the ratio of skin thickness to radius of curvature. Thus, the quantities to be measured at the "white knuckle" angle for blood flow occlusion are: (1) skin elongation, (2) skin thickness, and (3) radius of curvature.

HYPOTHESIS The central hypotheses of this project are that: (1) The skin blood flow of subjects who are prone to developing pressure sores will show a response to pressure loading which differs significantly from that of subjects who do not. (2) This difference can be detected by using simple controlled measurements and observations of the bent finger.

APPROACH We have made preliminary measurements of skin elongation using a finger goniometer. With the angle set to zero, two ink marks were made on the dorsal skin surface at a preselected initial length which spanned the knuckle. Measurements of length between the ink marks were then made for each selected angle of bend, using a flexible scale which was secured to the skin with scotch tape at the distal ink mark but was permitted to slide relative to the proximal mark. Measurements of skin thickness and radius of curvature were made using high-frequency echo doppler equipment, with the hand submerged in a water tank. A specially designed submersible fixture was used to fix both the angle of bend and the position of the finger relative to the ultrasound probe (see Figure 1).

From the limited number of able-bodied subjects studied to date, it appears that a typical skin elongation plot for an able-bodied subject is shown in Figure 2. The "effective" initial length l_0 for calculating skin elongation

Δl at blanching is obtained by extrapolating the straight-line portion of the elongation curve containing the white knuckle angle, all the way back to zero angle of bend (see Figure 2). The nondimensional elongation is then calculated as $\Delta l/l_0$.

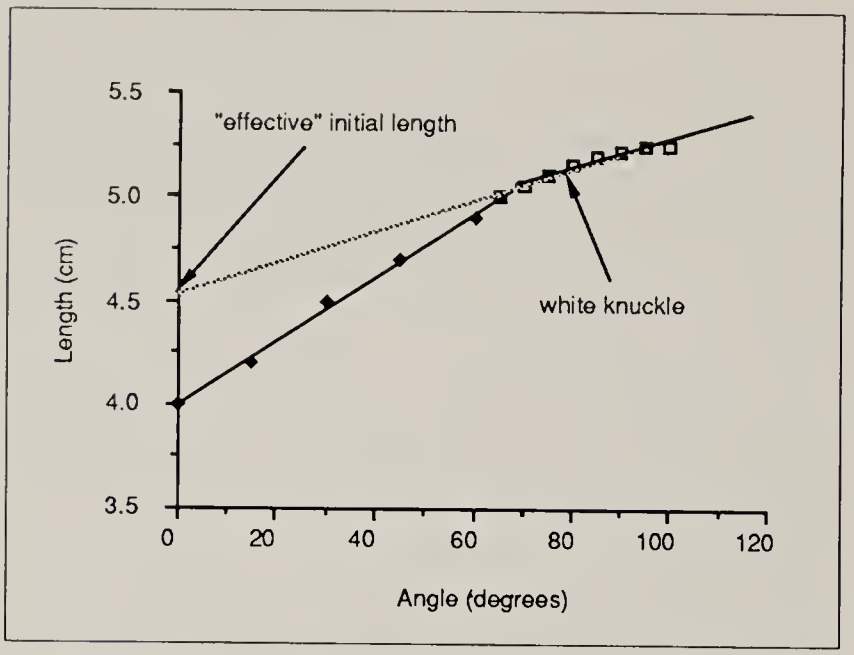

Figure 2. Skin elongation measurements on finger of able-bodied subject.

Some of our data have shown considerable scatter, presumably because the elongation measurement technique is not highly accurate. Nevertheless, the dimensionless ratio of pressure to elastic modulus at blood flow occlusion was found to be significantly lower in the paraplegics tested than for the able-bodied population.

This result means that a much lower pressure would be required to occlude capillary blood flow in paraplegics with the same skin elasticity. We also found significant differences for the values of skin elongation at occlusion between the two groups, which may allow us to screen patients without the need to make the ultrasound measurements at all!

STATUS Because of inaccuracies in the elongation measurement technique employed initially, and because only nine able-bodied subjects and six paraplegics have been tested to date, we plan to make use of a Pentax ME Super 35–mm camera and to design a camera and lighting mount which will accept the hand in a fixed position. This will enable us to take pictures of the bent finger under controlled conditions without contact of the dorsal skin surface. These pictures will be digitized for application of a curve smoothing program from which more precise and consistent measurements of skin elongation can be obtained.

PUBLICATIONS

Sacks AH. Skin behavior under load by the "white knuckle technique". *Proc 39th Ann Conf Eng Med Biol*, Baltimore, MD, 1986.

Sacks AH. The "white knuckle technique" for exploring skin behavior under load. *Proc 9th Ann Conf Rehabilitation Engineering (RESNA)*, Minneapolis, MN, 1986.

Sacks AH, O'Neill H. Skin response to pressure loading by the bent finger technique. *Proc 10th Ann Conf Rehabilitation Technology (RESNA)*, San Jose, CA, 1987.

SUPPORT

RR&D Core Resources

Alvin H. Sacks, PhD
Robert A. Weisgerber, EdD[1]
Richard D. Steele, PhD
Terry R. Armstrong, PhD[1]

Dissemination of Rehabilitation Technologies

PROBLEM Historically, there has been difficulty in maximizing the results of efforts by research and development teams to meet the needs of the disabled. It is clear that the technology transfer process is complex and dependent on many variables. In particular, the transfer of rehabilitation technology is complicated by such factors as:

(1) gaps in information flow between research and development staff, manufacturers, and consumers,
(2) the high cost of tooling, manufacturing, marketing and distribution in relation to the narrow market for many rehabilitation products, tending to discourage manufacture, and
(3) a lack of planning and coordination between the developers and suppliers of rehabilitation devices.

As a result, numerous good products never reach the market and are never used by their intended beneficiaries.

SIGNIFICANCE By enhancing the process of technology transfer we are better fulfilling the primary mission of the Center, which focuses on the delivery of rehabilitation findings, processes, and products that will directly benefit the disabled community. It is expected that this project will lead to a greater amount of coordination and cooperation between the Center and outside organizations and businesses, eventually leading to a higher rate of manufacture for products developed at the Center, as well as better dissemination of research findings beyond the research community.

BACKGROUND The VA has long recognized the need for publicizing its R&D efforts to develop technologies that can be used both in clinical practice and in the everyday living of the disabled individual. Prior to this project, limited attention has been given to formalizing the process, with the effect that transfer is facilitated by the decisions made throughout projects—from initial project conceptualization through prototype development.

HYPOTHESIS The central hypothesis of this study is that user acquisition and utilization of innovative technology could be improved if the entire system which researches, develops, manufactures, delivers, and maintains that technology were better understood, and if more effective transfer techniques were developed between the laboratory and the commercial sector.

APPROACH The approach we are taking involves:

(1) identifying critical steps that lead to effective transfer,
(2) codifying these steps and staff roles in a guidebook format,
(3) implementing those steps in the operational routine of scientists, engineers and other staff within the laboratory environment.

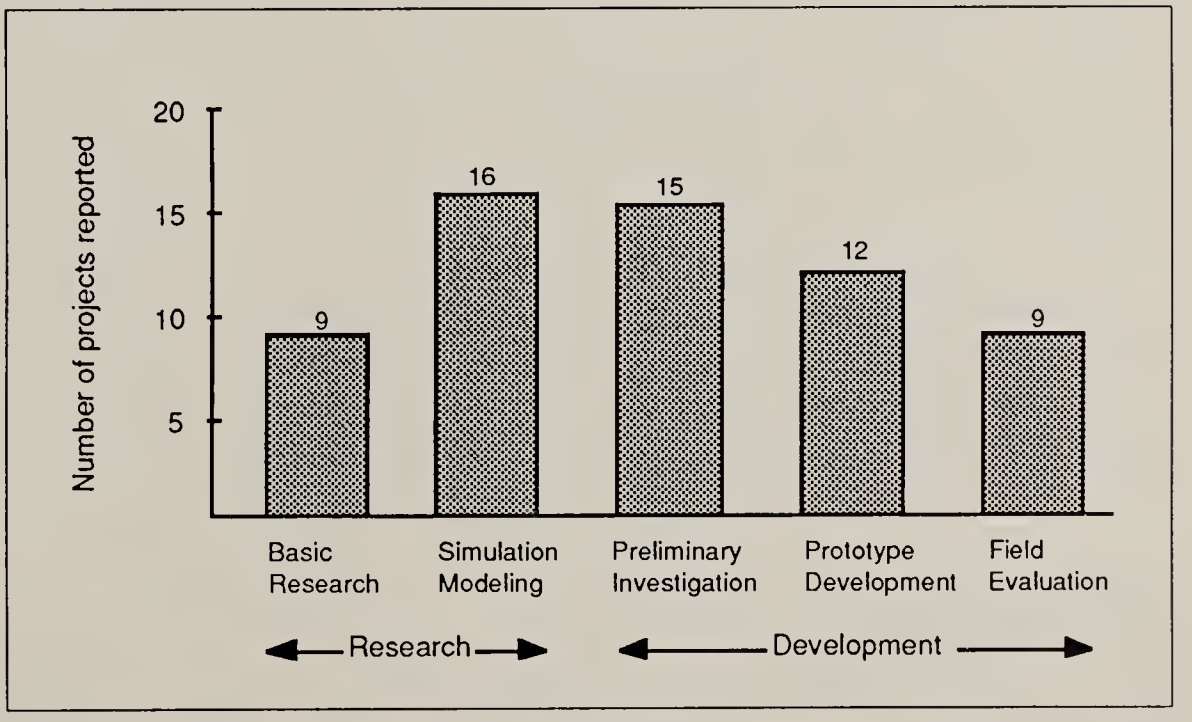

Figure 1. Profile of RR&D Center project types as characterized by investigators.

1. *American Institutes for Research*

The initial draft of the Technology Transfer Guidebook will have three versions—one for the use of investigators, one for use by the Center Director, and one for use by a designated Transfer Officer in the Center. During phase three, elements of the Guidebook will be field tested by using them on a trial basis in selected projects where transfer-related planning and decisions are being made. After appropriate revisions have been made, a final version of the Guidebook will be prepared and reproduced for ongoing use by VA staff. We also will share it with other VA facilities and Federal laboratories in the expectation that they will find it useful.

STATUS Information was collected in the first year in the form of:

(1) reviews of the literature on technology transfer,
(2) attendance at the 1986 RESNA conference, where various transfer models were described,
(3) interviews with four manufacturers of rehabilitation products, one manufacturer of robotic products, two service-provider organizations, three rehabilitation R&D organizations, and one research organization for technology transfer.

Interview data were analyzed with regard to nineteen variables that affect transfer and summarized in the first annual report prepared by American Institutes for Research (AIR).

In the second year a questionnaire was circulated to all R&D staff at the Center and an analysis was conducted of the range of research and development efforts underway. This analysis led to a profile of the Center's projects divided into four categories from theoretical investigations to applied product development. This distribution of project types is shown in Figure 1. In-depth, case-study interviews were then conducted with ten investigators representing this range of basic and applied studies.

The resulting information indicates that, for the most part, the staff have not yet focused on the importance of transfer as an aspect of their work, and even when they are aware of its importance are not familiar with the specific steps they can take to facilitate the process.

SUPPORT

VA RR&D Merit Review (1986-present)
RR&D Core Resources

STUDENT PROJECTS

Students are an integral part of the RR&D Center concept. Much of our productivity can be directly attributed to student projects advised by faculty who are associated with the Center. These projects have proven to be exceptionally effective in exploring new assistive device concepts. Through student pilot projects we often perform the preliminary studies from which merit review proposals are written and Center-staffed projects funded.

Beyond specific projects, we are fundamentally concerned with the education and training of engineers and physicians. It is our intent to give them the best possible technical learning experience in conjunction with exposure to the excitement and challenge of interdisciplinary research and development in rehabilitation. We expect to attract the best of the medical students and the best of engineering graduate students. While we involve many master's degree candidates in our projects, our primary concern is with the education of Rehabilitation Scientists, PhDs, and MDs specializing in rehabilitation. These people are the keystone for the study and development of rehabilitation as an academic endeavor.

Student involvement in RR&D Center projects is tabulated here. For each project, the students, faculty advisor, project course, and VA liasion are indicated. The association between individual students and Stanford contracts may be obtained from the university's accounting records. Note that students do not receive any salary or stipend for their work on student pilot projects. Research Assistants (RAs) do receive a stipend.

Liasion affiliation legend:

CHS REC	*Children's Hospital at Stanford Rehabilitation Engineering Center*
VA SCIS	*VA Spinal Cord Injury Service*
VA WBRC	*VA Western Blind Rehabilitation Center*

FISCAL YEAR 1978

Personal information system for the visually impaired.

Students	Greg Fowler, Engr (RA)
Advisor	Prof. John Linvill, PhD Prof. Martin Morf, PhD
Course	EE301, Engineering Special Problems (Thesis)
Liaison	Greg Goodrich, PhD, VA WBRC

Environmental control for quadriplegics.

Students	David Kelley, MS (RA) James Sachs, MS (RA)
Advisor	Prof. Larry Leifer, PhD
Course	ME 291, Individual Laboratory Projects
Liaison	Inder Perkash, MD, VA SCIS

Quantitative electromyography of the urethral sphincter.

Students	Edith Wilson, MS (RA)
Advisor	Prof. Larry Leifer, PhD
Course	ME291, Individual Laboratory Projects
Liaison	Inder Perkash, MD, VA SCIS

Exerciser for upper limb spasticity.

Students	Tom Woo, MS candidate Ken Allen, MS candidate Peter Axelson, BS candidate
Advisor	Prof. Philip Barkan, PhD
Course	ME210abc, Graduate Machine Design
Liaison	Inder Perkash, MD, VA SCIS

A modular seating and mobility system.

Students	Jonathan Flam, MS
Advisor	Prof. Robert McKim Prof. Larry Leifer, PhD
Course	ME211abc, Product Design Master's Project
Liaison	Inder Perkash, MD, VA SCIS Wally Mottlock, OP, CHS REC

A kitchen storage system for paraplegics.

Students David Lima, MS
Advisor Prof. Robert McKim
Prof. Larry Leifer, PhD
Course ME211abc, Product Design Master's Project
Liaison Inder Perkash, MD, VA SCIS
Christine Wright, OT, VA SCIS

Two-handled spoon development and evaluation.

Students Gregory Shaw, MS
Advisor Prof. Robert McKim
Prof. Larry Leifer, PhD
Course ME211abc, Product Design Master's Project
Liaison Christine Wright, OT, VA SCIS
Wally Mottlock, OP, CHS REC

Body barograph for measurement of surface pressure distributions.

Students Mary Springhorn, MS
John Kirby, MS
Tom Kinney, MS
Advisor Prof. Larry Leifer, PhD
Prof. Philip Barkan, PhD
Course ME210abc, Graduate Machine Design
Liaison Inder Perkash, MD, VA SCIS
Richard Ferdinand, PT, VA SCIS

Quadriplegic reacher.

Students JoAnne Bessler, BSPD
Dave Uken, BS
Advisor Prof. Larry Leifer, PhD
Course ME116c, Advanced Product Design
Liaison Inder Perkash, MD, VA SCIS
Christine Wright, PT, VA SCIS

Music synthesizer interface for the physically disabled.

Students Peter Aschenbrenner, BSPD
Advisor Prof. Larry Leifer, PhD
Course ME116c, Advanced Product Design
Liaison Christine Wright, PT, VA SCIS

Electronic games table for quadriplegics.

Students James Holmes, BS
Advisor Prof. Larry Leifer, PhD
Course ME116c, Advanced Product Design
Liaison Inder Perkash, MD, VA SCIS
Richard Ferdinand, PT, VA SCIS

A multiple-dose pill packaging system.

Students Carl Stern, BSPD
Tamiko Thiel, BSPD
William Shriver, BSPD
Advisor Prof. Larry Leifer, PhD
Course ME116c, Advanced Product Design
Liaison Ronald Sharp, Pharmacist, VAMC

A communication device for physically impaired adults.

Students Peggy Christiansen, BSPD
Advisor Prof. Larry Leifer, PhD
Course ME116c, Advanced Product Design
Liaison Sandi Enders, OT, CHS REC

Self feeder for cerebral palsy patients.

Students David Cannon, BS
Weston Press, BS
Robert Werle, BS
David Worms, BS
Advisor Prof. Ernest Chilton, PhD
Course ME113, Senior Machine Design
Liaison Wally Mottlock, OP, CHS REC

FISCAL YEAR 1979

Rehabilitation of neural transmission.

Students Gordon Abraham, MS, PhD candidate (RA)
Advisor Prof. Bernard Widrow, PhD
Prof. Larry Leifer, PhD
Course EE29, Individual Laboratory Projects
Liaison Rodney Hentz, MD, VA Reconstructive Surgery

Rehabilitation of urethral muscle function.

Students Stephan Jacklin, MS (RA)
Advisor Prof. Larry Leifer, PhD
Course ME291, Individual Laboratory Projects
Liaison Inder Perkash, MD, VA SCIS

Structural properties of bone and connective tissue.

Students Elizabeth Meyer, MS, PhD candidate (RA)
Advisor Prof. Robert Piziali, PhD
Course ME291, Individual Laboratory Projects
Liaison Donald Nagel, MD, Orthopaedic Surgery, Stanford

Head-control unit for piloting a robotic arm.

Students William Shriver, MS
Paul Justle, MS
Steve Tipton, MS
Advisor Prof. Larry Leifer, PhD
Prof. Philip Barkan, PhD
Course ME210abc, Graduate Machine Design
Liaison Inder Perkash, MD, VA SCIS
Richard Ferdinand, PT, VA SCIS

Body barograph for measurement of surface pressure distributions (continuing).

Students Mary Springhorn, MS
John Kirby, MS
Tom Kinney MS
Advisor Prof. Larry Leifer, PhD
Prof. Philip Barkan, PhD
Course ME210abc, Graduate Machine Design
Liaison Inder Perkash, MD, VA SCIS
Richard Ferdinand, PT, VA SCIS

No-grasp reacher.

Students William Scott, MFA
Hal Kent, BS
Advisor Prof. Robert McKim
Prof. Larry Leifer, PhD
Course ME211abc, Product Design Master's Project
Liaison Christine Wright, OT, VA SCIS

Upper-limb ergometer compatible with wheelchair and bed usage.

Students Mike Barker, MS
Jim Dornbusch, MS
Humberto Rincon, MS
Advisor Prof. Larry Leifer, PhD
Prof. Philip Barkan, PhD
Course ME210abc, Graduate Machine Design
Liaison Inder Perkash, MD, VA SCIS
Richard Ferdinand, PT VA SCIS

A walk-in bathing system for elderly individuals.

Students BoFat Chan, MFA
Advisor Prof. Robert Mckim
Prof. Larry Leifer, PhD
Course ME211abc, Product Design Master's Project
Liaison Christine Wright, OT, VA SCIS

Wheelchair design study.

Students David Willis, MFA
Advisor Prof. Robert McKim
Prof. Larry Leifer, PhD
Course ME211abc, Product Design Master's Project
Liaison Richard Ferdinand, PT, VA SCIS
Wally Mottlock, OP, CHS REC

No-grasp door opener for quadriplegics and persons with arthritis.

Students Lee Winick, BSPD
Advisor Prof. Larry Leifer, PhD
Course ME116c, Advanced Product Design
Liaison Christine Wright, OT, VA SCIS

The arroya downhill ski-sledding system for paraplegics.

Students Peter Axelson, BSPD
Advisor Prof. Larry Leifer, PhD
Course ME116c, Advanced Product Design
Liaison Inder Perkash, MD, VA SCIS
Robert Montero, MD, VA PM&R

FISCAL YEAR 1980

Development and evaluation of a robotic aid.

Students Charles Wampler, MS, PhD candidate (RA)
John Jameson, MS, PhD candidate (RA)
Charles Buckley, MS, PhD candidate (RA)
Rickson Sun, MS, EngrD candidate (RA)
Advisor Prof. Larry Leifer, PhD
Course ME301, Thesis Research
Liaison Inder Perkash, MD, VA SCIS

Rehabilitation of neural transmission (continuing).

Students Gordon Abraham, MS, PhD candidate (RA)
Advisor Prof. Bernard Widrow, PhD
Prof. Larry Leifer, PhD
Course EE291, Individual Laboratory Projects
Liaison Rodney Hentz, MD, VA Reconstructive Surgery

Rehabilitation of urethral muscle function (continuing).

Students Stephan Jacklin, MS (RA)
Advisor Prof. Larry Leifer, PhD
Course ME291, Individual Laboratory Projects
Liaison Inder Perkash, MD, VA SCIS

Structural properties of bone and connective tissue (continuing).

Students Elizabeth Meyer, MS, PhD candidate (RA)
Advisor Prof. Robert Piziali, PhD
Course ME291, Individual Laboratory Projects
Liaison Donald Nagel, MD, Orthopaedic Surgery, Stanford

On the feasibility of robotic aids for the severely disabled.

Students Charles Buckley, MS, PhD candidate (RA)
Advisor Prof. Larry Leifer, PhD
Course ME291, Individual Laboratory Projects
Liaison Inder Perkash, MD, VA SCIS

Human knee mechanics associated with gait and support problems.

Students David Fyhrie, MS, PhD candidate (RA)
Advisor Prof. Robert Piziali, PhD
Course ME219, Individual Laboratory Projects
Liaison Donald Shurman, MD, Orthopaedic Surgery, Stanford

Sensate robotic hand.

Students Rickson Sun, MS
Advisor Prof. Larry Leifer, PhD
Prof. Robert McKim
Course ME211abc, Product Design Master's Project
Liaison Rodney Hentz, MD, VA Hand Surgery Center

Bicycle for paraplegics.

Students Douglas Schwandt, MS
Candy Mintz, MS
Advisor Prof. Larry Leifer, PhD
Prof. Philip Barkan, PhD
Course ME210abc, Graduate Machine Design
Liaison Inder Perkash, MD, VA SCIS
Richard Ferdinand, PT, VA SCIS
Peter Axelson, BS, RR&D Center

Smart wheelchair.

Students Karen Altman, MS
Richard Epstein, MS
Leslie Gerding, MS
Wayne Leger, MS
David Parker, MS
Advisor Prof. Larry Leifer, PhD
Prof. Philip Barkan, PhD
Course ME210abc, Graduate Machine Design
ME218ab, Smart Product Design
Liaison David Jaffe, MS, RR&D Center

Orientation algorithm for sensate hand.

Students Jim Woodward, MS
Walter Hardt, MS
Angio Jaccard, MS
Advisor Prof. Bernard Widrow, PhD
Prof. Larry Leifer, PhD
Course EE280ab, Computer Applications Laboratory
Liaison David Jaffe, MS, RR&D Center
Rickson Sun, MS

Upper limb ergometer.

Students James Sacherman, BSPD
Advisor Prof. Larry Leifer, PhD
Course ME116c, Advanced Product Design
Liaison Inder Perkash, MD, VA SCIS
Christine Wright, OT, VA SCIS
Richard Ferdinand, PT, VA SCIS

FISCAL YEAR 1981

Development and evaluation of a robotic aid (continuing).

Students Charles Wampler, MS, PhD candidate (RA)
John Jameson, MS, PhD candidate (RA)
Charles Buckley, MS, PhD candidate (RA)
Advisor Prof. Larry Leifer, PhD
Course ME301, Thesis Research
Liaison Inder Perkash, MD, VA SCIS

Human factors at the man-computer interface.

Students Richard Vistnes, MSCS, PhD candidate (RA)
Advisor Prof. Thomas Binford, PhD
Prof. Larry Leifer, PhD
Course ME291, Individual Laboratory Projects
Liaison Inder Perkash, MD, VA SCIS

Microcomputer controller for the smart wheelchair.

Students Thomas Vink, MS, PhD candidate (RA)
Advisor Prof. Larry Leifer, PhD
Course ME291, Individual Laboratory Projects
Liaison David Jaffe, MS, VA RR&D

Structural properties of bone and connective tissue.

Students Ataullah Arjomand, MS, PhD candidate (RA)
Advisor Prof. Robert Piziali, PhD
Course ME291, Individual Laboratory Projects
Liaison David Shurman, MD, Orthopaedic Surgery, Stanford

Understanding of human pitch perception.

Students Mitchel Weintraub, MS, PhD candidate (RA)
Advisor Prof. Joseph Goodman, PhD
Course EE301, Thesis Research
Liaison Prof. Earl Schubert, MD, Surgery, Stanford

A six-degree-of-freedom manipulandum for remote manipulation.

Students Machiel Van der Loos, DiplEngr, Engr candidate (RA)
Advisor Prof. Larry Leifer, PhD
Course ME301, Thesis Research
Liaison Inder Perkash, MD, VA SCIS

Human knee mechanics associated with gait problems (continuing).

Students David Fyhrie, MS, PhD candidate (RA)
Advisor Prof. Robert Piziali, PhD
Course ME219, Individual Laboratory Projects
Liaison Donald Shurman, MD, Orthopaedic Surgery, Stanford

Modeling neuromuscular stimulation of the upper extremity.

Students Felix Sheu, MS, PhD candidate (RA)
Advisor Prof. Felix Zajac, PhD
Course ME291, Individual Laboratory Projects
Liaison Ronald Angel, MD, VA Neurology

Omnidirectional robot mobility base.

Students Mike Hightower, MS
John Reinersten, MS
Richard Steidle, MS
Advisor Prof. Larry Leifer, PhD
Prof. Philip Barkan, PhD
Course ME210abc, Graduate Machine Design
ME218ab, Smart Product Design
Liaison William La, PhD, VA RR&D
Timothy Koogle, EngrD, VA RR&D
Brian Carlisle, MS, Unimation Inc.
Donald Allen, MS, Unimation Inc.

Stimulus artifact suppression in nerve action potential recording.

Students Bruno Berlizot, MS
Kelley Leutkmeyer, MS
Dwight Nishimura, MS
Advisor Prof. Bernard Widrow, PhD
Course EE280, Computer Applications Laboratory
Liaison Kenneth Cummins, PhD, VA RR&D
Leslie Dorfman, MD, VA RR&D, Stanford Neurology
Kevin McGill, PhD candidate

Total fitness system.

Students James Sacherman, MS
Advisor Prof. Robert McKim
Prof. Larry Leifer, PhD
Course ME211abc, Product Design Master's Project
Liaison Inder Perkash, MD, VA SCIS
John Riccaro, PT, VA SCIS

A product to promote aerobic fitness.

Students David Uken, MS
Advisor Prof. Robert McKim
Prof. Larry Leifer, PhD
Course ME211abc, Product Design Master's Project
Liaison David Pliskin, MS, VA RR&D

A digital pager for the hearing impaired.

Students Tom Rhodes, MS
Advisor Prof. Larry Leifer, PhD
Course ME218ab, Smart Product Design
Liaison Richard Goode, MD, Ear, Nose and Throat Surgery

Talking thermometer.

Students Hans Christian Engelhardt, MS
Advisor Prof. Larry Leifer, PhD
Course ME218ab, Smart Product Design
Liaison Gregory Goodrich, PhD, VA WBRC
Dianne Morrissette, VA WBRC

Easy rising chair.

Students Richard Morrison, MS
Advisor Prof. Robert McKim
Course ME211abc, Product Design Master's Project
Liaison Robert Montero, MD, VA PM&R

FISCAL YEAR 1982

Development and evaluation of a robotic aid (continuing).

Students Charles Wampler, MS, PhD candidate (RA)
John Jameson, MS, PhD candidate (RA)
Charles Buckley, MS, PhD candidate (RA)
Walter Conti, BS, MS candidate (RA)
Michael Van der Loos, DiplEngr, PhD candidate (RA)
Advisor Prof. Larry Leifer, PhD
Course ME301, Thesis Research
Liaison Inder Perkash, MD, VA SCIS

Detection of images of print in natural scenes.

Students Dean Hennies, BS
Eric Schoen, MS
Joe Atterbury, BS
Syed Hassan, MS
Advisor Prof. Bernard Widrow, PhD
Course EE280, Computer Applications Laboratory
Liaison Sally Wood, PhD, VA RR&D
Stuart McDonald, BA, VA RR&D

Biophysical factors affecting nerve conduction velocity.

Students A.B. Danda, MSBio/BS
Advisor Prof. Donald Perkel, PhD
Course Neurology 199, Directed Study
Liaison Kenneth Cummins, PhD, VA RR&D

Orator—a speech synthesis aid for the non-vocal.

Students Steven Lee, MS
Michael Nelson, MS
Advisor Prof. Larry Leifer, PhD
Course ME218abc, Smart Product Design
Liaison Richard Steele, PhD, VA RR&D
Sally Wood, PhD, VA RR&D
Peggy Barker, MSRE, CHS REC

Head-high obstacle detector.

Students Steve Bayer, MS
Tom Saxe, MS
Advisor Prof. Larry Leifer, PhD
Course ME218abc, Smart Product Design
Liaison David Jaffe, MS, VA RR&D
Diane Morrissette, VA WBRC
Sue Melrose, VA WBRC

Automated clinical exercise management system.

Students Peter Axelson, MS
Alan Masters, MS
Advisor Prof. Felix Zajac, PhD
Prof. Larry Leifer, PhD
Course ME218abc, Smart Product Design
Liaison Ron Gaines, MD, VA SCIS
David Dungan, VA RR&D
David Jaffe, MS, VA RR&D
Fred Lakin, MFA, VA RR&D

A robot hand with vision capability.

Students Roger Ackerman, MS
Kenji Mori, MS
Advisor Urs Elsasser, Ph.D, Research Associate
Prof. Philip Barkan, PhD
Course ME210abc, Graduate Machine Design
Liaison Larry Leifer, PhD, VA RR&D

Leg circumference measurement support.

Students LuAnn Piccard, BS
Advisor Prof. David Kelley
Course ME116c, Advanced Product Design
Liaison David Dungan, VA RR&D
Barbara Jones, PT, VA SCIS

FISCAL YEAR 1983

Detection of images of print in natural scenes.

Students Dean Hennies, MS
Advisor Prof. Bernard Widrow, PhD
Course EE280, Computer Applications Laboratory
Liaison Sally Wood, PhD, VA RR&D

Video instruction system for the disabled.

Students Joseph P.H. Chan, MS
John C. Tang, MS
Michael Ott Trainor, BS
Advisor Gayle Curtis, MS
Course ME 218abc, Smart Product Design
Liaison K.G. Engelhardt, BA, VA RR&D

FISCAL YEAR 1984

Development of a camera for use in sensory aids for the blind.

Students Jay Duluk, MS, PhD candidate (RA)
Dan Gerrity, MS, PhD candidate (RA)
Christopher Hughes, BS candidate (RA)
Joanne Wilson, MS, PhD candidate (RA)
Advisor Prof. Bernard Widrow, PhD
Course EE280, Computer Applications Laboratory
Liaison Richard Steele, PhD, VA RR&D
Dean Hennies, MS, VA RR&D

Human interface for emergency alert systems.

Students 16 upper division BS and MS candidates in product design
Advisor Prof. William Moggridge
Course ME 116a, Advanced Product Design.
Liaison Karen Holloway, BS, VA RR&D
K.G. Engelhardt, BA, VA RR&D

Needfinding for the elderly.

Students 20 upper division BS and MS candidates in product design
Advisor Prof. William Verplank, PhD
Course ME 116b, Needfinding in Product Design
Liaison K.G. Engelhardt, BA, VA RR&D
Karen Holloway, BS, VA RR&D
Walter Vogel, MD, volunteer

Effects of gender in work with the robotic aid.

Students Carol Jennings, BA
Advisor Prof. Sanford Dornbusch, PhD
Prof. Larry Leifer, PhD
Course Human Biology Honors Thesis
Liaison Karen Holloway, BS, VA RR&D

Impact of differential training in work on a robotic device.

Students Dorinda Marticorena, BA
Advisor Prof. Sanford Dornbusch, PhD
Prof. Larry Leifer, PhD
Course Human Biology Honors Thesis
Liaison Karen Holloway, BS,VA RR&D

FISCAL YEAR 1985

Development of a camera for use in sensory aids for the blind.

Students Chris Fernquest, MS candidate
An-ni Huynh, MS candidate
Ken McMillan, MS, PhD candidate
Mark Santoro, MS, PhD candidate
Advisor Prof. Bernard Widrow, PhD
Course EE280, Computer Applications Laboratory
Liaison Richard Steele, PhD, VA RR&D
Dean Hennies, MS, VA RR&D
Jay Duluk, MS, VA RR&D

Mediminder: a problem in medication packaging.

Students 24 upper division BS and MS candidates in product design
Advisor Prof. William Moggridge
Course ME 116a, Advanced Product Design
Liaison Karen Holloway, VA RR&D

Breakaway table for a robotic testing environment.

Students Cyndie Benjamin, BS
Denny Dart, BS
Advisor Prof. Larry Leifer, PhD
Course ME 191, Independent Study
Liaison Karen Holloway, BS, VA RR&D
Stefan Michalowski, PhD, VA RR&D and Stanford
Machiel Van der Loos, EngrD, VA RR&D and Stanford

Finger spelling hand.

Students John Danssaert, BS, MS candidate
Alan Greenstein, BS, MS candidate
Patricia Lee, BS, MS candidate
Alex Meade, BS, MS candidate
Advisor Prof. Charles Buckley, PhD
Prof. Philip Barkan, PhD
Course ME210abc Graduate Machine Design
Liaison David L. Jaffe, MS, VA RR&D

FISCAL YEAR 1986

Development of a walking chair.

Students Andrew Bennet, BS, MS candidate
Brian Nass, BS, MS candidate
Bill Wilcox, BS, MS candidate
Mark Zbarachi, BS, MS candidate
Advisor Prof. Larry Leifer, PhD
Prof. Philip Barkan, PhD
Course ME210abc, Graduate Machine Design
Liaison Machiel Van der Loos, EngrD, VA RR&D, Stanford
David L. Jaffe, MS, VA RR&D

FISCAL YEAR 1987

Manual wheelchair drive and controls for improved efficiency.

Students B.J.Fregly, BS, MS candidate
Tim Garrison, BS, MS candidate
Harry Martins, BS, MS candidate
Lynette Ross, BS, MS candidate
Advisor Prof. Philip Barkan, PhD
Course ME210abc Graduate Machine Design
Liaison Douglas Schwandt, MS, VA RR&D
Eric Sabelman, PhD, VA RR&D

Clothing fasteners for people with hand and arm limitations.

Students 25 upper division BS and MS candidates in product design
Advisor Prof. William Moggridge
Course ME 116a, Advanced Product Design.
Liaison Karen Holloway, BS, VA RR&D

The expressive potential of a robotic arm in an interactive environment.

Students Pamela Greene, MFA
Advisor Prof. David Kelley
Course ME 211b/Art360, Product Design Master's Project
Liaison Gayle Curtis, MS, VA RR&D

FISCAL YEAR 1988

Self-operated lift for the disabled.

Students Michael Butler, BS, MS candidate
Stephanie Moore-Fuller, BS, MS candidate
David Snow, BS, MS candidate
Advisor Prof. Saadia Bahat
Course ME210abc, Graduate Machine Design
Liaison Eric Sabelman, PhD, VA RR&D

Comparison of methods for analyzing electromyography.

Students Kalai Lau, BS candidate
Stan Sze, BS candidate
Advisor Prof. Leslie Dorfman, MD
Course Biology 191, Special Project
Liasion Kevin McGill, PhD, VA RR&D

FACILITIES

The RR&D Center is based in a building on the Palo Alto VA Medical Center campus which contains office space for administrative and technical staff, a conference area, laboratory space, computer facilities, and a machine shop. In addition, several other laboratory facilities at the VA Medical Center and at Stanford University are closely involved in RR&D Center projects. This section describes the facilities of the RR&D Center and the associated laboratories.

REHABILITATION RESEARCH AND DEVELOPMENT CENTER

The RR&D Center is located in building 51 of the Palo Alto VA Medical Center, adjacent to the Spinal Cord Injry Service and near the Western Blind Rehabilitation Center. The 80' by 80' Butler building was occupied in June, 1980, and dedicated on September 12, 1980. Space within the building is allocated as follows:

Sq.ft.	Usage
1600	workstations (30)
740	neuromuscular laboratories (includes 3 workstations)
224	computer workstation room (includes 3 workstations)
416	project laboratories (3, includes 4 workstations)
340	computer equipment room
572	prototyping facility (includes 1 workstation)
280	conference area (includes 1 workstation)
800	physical plant, restrooms, housekeeping
1428	corridors, ramps, etc.
6400	total

The building is outfitted with open modular landscape furnishings, which provide a flexible and cost-effective means to alter the interior areas as needed. All utilities are routed under access flooring. An 8000 square foot addition is under construction.

The principal RR&D Center facilities in building 51 and elsewhere on the VA Medical Center campus are listed below.

NEUROMUSUCLAR BIOMECHANICS LABORATORY

Rehabilitation R&D Center, PAVAMC.

Purpose The Neuromuscular Biomechanics Laboratory supports research on coordination of human lower extremity muscles during posture, walking, and pedaling in able-bodied and disabled persons.

Resources

Kinetic and kinematic monitoring system

Selcom Selspot II movement-monitoring system:
- infrared cameras with 50mm lenses (2)
- measurement diodes (16)
- 312 Hz frame sampling rate

Advanced Mechanical Technology ground-reaction force-plate system:
- 2 adjacent force plates, each plate capable of monitoring three forces and moments
- analog signal conditioning.

Bipedaling apparatus

A stationary Monark ergometer is modified and connected to a custom-built gearing system and seating frame. The two pedal cranks are decoupled with each one chain-linked to a common load crank. The system can be configured so that the legs pedal either at a fixed phase with respect to one another (0 to 360 deg), or at different speeds. Also, one leg can be forced to pedal in either the same or different direction as the other. The pedal and crank angles are measured with potentiometers. Two pedal dynamometers transduce the vertical and anterior-posterior forces exerted on each pedal.

Signal acquisition and analysis equipment
EMG telemetry system: LM Electronics FM transmitting and receiving units (12 channels)
EMG recording amplifiers: Grass P511 AC-coupled high-impedance amplifiers (14 channels)
Instrumentation tape recorder: EMI model 7000 SE (14 channels) Kode model 275 time-code/tape-search unit IEEE-488 computer interface
Siemens Mingograf high-speed paper inkwriter (8 channels)
Bidirectional hard-wire A/D, D/A, and D/D link to RR&D Center computer facility (90 channels)
Tektronix 5103 oscilloscopes (2)
Graftek 2400 x-y recorder
Ortek 4710 dual-channel programmable pulse generator.

NEUROMUSCULAR ELECTROPHYSIOLOGY LABORATORY

Rehabilitation R&D Center, Palo Alto VA Medical Center (PAVAMC).

Purpose The Neuromuscular Electrophysiology Laboratory is used for collecting and analyzing human neuromuscular electrophysiology data. Its capabilities parallel those of the Stanford Laboratory of Electromyography.

Resources
TECA AA6Mk2 amplifiers/preamps (2)
Gould strain gauges (2) with load cells and DC amplifier/display
Technical Manufacturing Corp. vibration-isolated table
Tektronix 5031 and 5103 oscilloscopes
Nicolet digital oscilloscope
Ortec programmable stimulators (2)
Bak Electronics biphasic stimulus isolators (2)
AMP Inc. patch-panel interconnection system
Grass AC-coupled high-impedance recording amplifiers (6)
Grass audio monitor
EMI 7000 SE instrumentation tape recorder (14 channels)
Bidirectional hard-wire A/D, D/A and D/D links to RR&D computer
Visual 550 graphics terminal.

CLINICAL ROBOTICS LABORATORY

Spinal Cord Injury Center, PAVAMC.

Purpose The Clinical Robotics Laboratory (CRL) supports the clinical evaluation and training portions of the Robotic Aid Project (RAP). The enclosed lab space supplies an environment for speech-related studies being done in the context of the project. This lab also provides office space for some of the researchers involved. The equipment below is used in two complete robotic evaluation systems. One supports daily-living tasks, the other vocational tasks.

Resources
LSI-11/73 based PUMA arm controllers (2)
PUMA-260 6-axis robot manipulators (2)
Heavy-duty mobile work surface robot arms (2)
Otto-Bock 'Greiffer' prosthetic grippers (2)
Votan voice recognition units (2)
Equipment rack for robot electronics
IBM AT microcomputer systems (2)
IBM CGA & PGA monitors
IBM Pro-printer
Tape backup subsystem
Introvoice voice recognition system
Amdek color monitor
Amdek monochrome monitors (2)
NEC & Samsung color monitors
Heathkit X-10 Environment Control Unit
Sears microwave ovens (2) for robot applications
Sears refrigerators (2) for robot applications.

PROTOTYPING FACILITIES

Rehabilitation R&D Center, PAVAMC.

Purpose These facilities provide in-house capabilities to fabricate and modify prototypes.

Resources
Electronics facility
Oscilloscopes: Tektronix SC503, 465M, 7623A, 7603, Nicolet 2090-III
Digital voltmeters: Tektronix DM502A; Fluke 8022A 8024A
Analyzer: Nicolet 800A
Function generators: Tektronix FG502, FG504
Universal bridge: Hewlett-Packard 4260A
Transistor analyzer: Sencore
Capacitance meter: B-K 820
Prom programmer: Data I/O System 19

Logic probes, power supplies, breadboards, wire-wrapping tools.

Machine facility
Metal
Bridgeport Series I milling machine with digital readout
Southbend 10 toolroom lathe
drill presses
spot and gas welding equipment
20" bandsaw
plus a wide variety of attachments
Sheet Metal
52" pneumatic shear
48" box break
power hand shears
Wood
bandsaw
radial arm and table saws
jointer
General
grinders, sander, circular saw, abrasive machine (belt & disc)
solvent bath, air compressor, power drills, vises, reamers, precision measuring tools, force gages.

COMPUTER FACILITY

Rehabilitation R&D Center, PAVAMC.

Purpose The DEC VAX-11/780 minicomputer is the principal computational resource for the RR&D Center. It is used by all Center personnel for electronic mail and text processing. It is also used for scientific computations, including finite element analyses for orthopaedic biomechanics and simulations of electrophysiological signals and of musculoskeletal dynamics. In addition, the VAX is used for budget preparation, accounting, and internal inventory control.

A number of other minicomputers are used for special purpose applications. The DEC PDP-11/34 minicomputer is used for real-time acquisition of experimental data, including clinical electromyograms and kinesiological data associated with muscle-coordination studies. The Silicon Graphics IRIS 2400 minicomputer is used for displaying the results of musculoskeletal simulations. The Symbolics 3650 computer is being used to develop a natural-language interface for the robotic aid project.

There are also a number of IBM and Apple Macintosh microcomputers at the Center, which are used for document preparation, technical illustration, spread sheet calculations, and statistical data analyses. Several other stand-alone microcomputer systems are used for developing microcomputer-based assistive devices. The desktop publishing system described below was used to produce camera-ready copy for this Progress Report.

Resources
VAX-11/780 computer
Hardware
32 bit processor
Floating point accelerator
16 Mbytes main memory
80 terminal lines
2 high speed inter-processor communication lines (DMC11)
1 Gbyte mass storage
High-resolution printer/plotter (QMS Lasergrafix 1200)
17x22" bed plotter (Tektronix 4663)
2 digitizers
Software
VMS operating system
Fortran-77, Pascal, Forth, Lisp, Assembly, C languages
Vax/VMS-68000 cross-compilers for C and Pascal
VMS/CPM software emulation
EDT, EDI, SOS, TECO, EMACS editors
DataTrieve data-base system
Interactive Laboratory System
Versaplot, IGL plotting packages
TeX typesetting language
Abaqus, Ansys, Gifts, Femgen/Femview finite element analysis/modeling packages
DecNet interprocessor communication.

PDP-11/34 computer
Hardware
16 bit processor
Floating point processor
256 Kbytes main memory
Cache memory
75 ips nine track tape drive
67 Mbyte mass storage device (RM02)
2 5-Mbyte and 1 10-Mbyte mass storage devices (RL)
IEEE-488 (GPIB) interface
Laboratory Peripheral Accelerator (LPA11)
16-channel A/D converters (2)

4-channel D/A converter (AA11-K)
Dual programmable real time clocks (KW11-K) (2)
16 DMA D/D controller (DR11-B)
16 bit D/D controller (DR11-K) (2)
High speed and low speed inter-processor links
Software
RSX11-M and RT-11 operating systems
Fortran IV-Plus, Pascal, Forth, Assembly languages
EDT, EDI, EDX, TECO editors
Selspot three-dimensional monitoring package
DecNet interprocessor communication.

Symbolics 3650 computer
Hardware
32 bit word,
8 MByte memory,
370 MByte mass storage,
1/4 inch tape drive,
Ethernet access
Software
LISPM operating system, Fortran.

Silicon Graphics IRIS 2400 computer
Hardware
32 bit word,
4 MByte memory
256 MByte mass storage
1/4 inch tape drive
Software
Unix operating system, Fortran, C.

Microcomputers
Hardware
Z-80 systems (5),
IBM PC XT/AT systems (4),
A variety of A/D, D/A and D/D converters, monitors, communication interfaces, and printers.
Apple MacIntosh/MacintoshII systems (12).
MacVision video digitizer
ThunderScan digitizer
Radius Full Page Display
LaserWriter Plus laser printers (2)
Software
CP/M, DOS, Macintosh operating systems
Fortran IV, Pascal, Forth, Lisp, CoralCommonLisp, Basic languages
ED, PIE, Wordstar, WriteNow editors
MacProject, MORE, Microsoft Excel, project planning tools
MacTerminal, VersaTerm terminal emulators.

Desktop Publishing system
Hardware
Apple Macintosh II with
2 Mbyte memory
40 Mbyte hard disk
13" color monitor
LaserWriter Plus
Software
Ready,Set,Go!4 page layout program
Microsoft Word, MacWrite, word processors
Adobe Illustrator, MacDraw, MacDraft, SuperPaint, CricketDraw, CricketGraph technical illustration tools

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STANFORD UNIVERSITY FACILITIES

Several RR&D Center projects make use of laboratory facilities at Stanford University and at Stanford University Medical Center. The Stanford facilities currently involved with RR&D Center projects are listed below.

CENTER FOR DESIGN RESEARCH

Building 530, Stanford University.

Purpose The Center for Design Research (CDR) is dedicated to facilitating individual creativity, understanding the design process, and developing superior products using advanced manufacturing systems. At CDR, students and investigators create state-of-the-art product prototypes that range from mobile robots to gravity probe satellites and space suit prehensors.

User-transparent computer system instrumentation will allow study of how people use design tools, access design information data bases, and synthesize their thoughts for communication within the computer environment. There is a strong emphasis on human factors, product simulation, rapid prototyping, and manufacturing for the full product "life cycle". The approach is integrative with special attention to visualization (human and machine), modeling (analytic and physical), and communication between design, manufacturing, and management processes.

Resources
IBM 4341-12 medium-scale computer
32 bit word

16 MByte memory
7.5 GByte mass storage
Magnetic tape drives (2)
Color graphic workstations (1024x1024 pixel, 256 colors) (10)
Monochrome caligraphic workstations (6)
Pen plotter (E-size)
Laser printer (1)
Page printers.

Sun 3/260c computer
32 bit word
8 MByte memory
High-resolution color graphics display
141 MByte mass storage
1/4 inch tape drive.

Sun 3/160 computer
32 bit word
16 MByte memory
High-resolution color graphics display
456 MByte mass storage
1800/1600 bpi tape drive.

Symbolics 3645 computer
32 bit word
8 MByte memory
370 MByte mass storage
1/4 inch tape drive.

DEC MicroVAX computer (2)
32 bit word
2 MByte memory
456 MByte mass storage.

Workstations
IBM PC/XT (8)
IBM PC/AT (8)
Macintosh (9).

Manipulators
PUMA 250 (4)
PUMA 500 (1)
ASEA (1)
ADEPT (1)
IBM RS1 (1)
IBM 7535 (1).

Operating systems
VM/HPO - CMS (IBM)
VMS (DEC)
UNIX (Sun, Silicon Graphics)
LISPM (Symbolics).

Networks
CSnet
BITnet
ARPAnet
SUNet (Stanford University ethernet interface).

Languages
Fortran, C, Assembler, Prolog, C, Pascal/VM
Pascal/Micro-power (real-time), PL/I
Common Lisp, Lisp/VM, PSLisp
Fortran compatibility package under development
Graphics workstation interface under development
MacLISP compatibility package.

Major engineering packages
CADAM (computer augmented design and manufacturing)
CATIA (solid modeling)
PATRAN (finite element modeling)
NC130 (3+ axis milling)
NC300 (lathe controller)
PL110, PL200, PL300 (mold flow graphics interface)
SH100, SH200 (sheet metal design and punch),
MRS (knowledge engineering development system)
IBM ESE/VM (knowledge engineering development system).

INTERACTIVE ROBOTICS LABORATORY

Building 530, rooms 530 & 534, Stanford University.

Purpose The Interactive Robotics Laboratory (IRL) is a facility within the Center for Design Research which supports a variety of research and development projects concerned with the development of practical manipulation systems for severely disabled persons. The projects in IRL deal primarily with man-machine integration and the sensory interaction between a manipulator and its environment.

Resources

1000 square feet of laboratory space.

9-DOF prototype robotic aid
Omnidirectional mobile base
PUMA-250 robotic arm
Proximity-sensing hand
Force-sensing wrist
Segmented bumper
LSI11/73 microprocessor with peripherals
KXT11-C peripheral processor
4800-baud serial radio link

CCD television camera and UHF transmitter
2-channel emergency radio link
Tandy 200 computer, keyboard, LCD display.

Prototype robot control console
IBM PC/AT computer
IBM Professional Graphics Adaptor and color monitor
IBM Color Graphics Adaptor and color monitor
Sharp 9-inch color TV receiver
Ultrasonic head position detector
Kurzweil speech recognition unit
DECTALK speech output unit
4800-baud serial radio link
2-channel emergency radio link.

3-DOF prototype robotic aid
Omnidirectional mobile base
7-axis joystick and radio controller.

6-DOF Unimation PUMA-260 manipulator
6-DOF Unimation PUMA-560 manipulator
LSI-11/2 based arm controllers (2).

DEC PDP 11/23 development system
256K byte main memory
RK01 disk drives (2 @ 5M-bytes each)
30 Mbyte Winchester hard disk with 8" floppy backup
4-channel serial interface
VT100 terminal.

MicroVAX II minicomputer
8-MB main memory
Fujitsu Eagle 450-MB hard disk
5-inch floppy disks (2)
8-channel serial interface
DEQNA Ethernet interface
Apple Laserwriter printer
1200-baud modem
Ann Arbor XL terminal.

Apple Lisa & Macintosh Computers
IBM PC/AT & XT computers
Nicolet digital oscilloscope
Intech logic analyzer
Uniphase 1108P He-Ne laser with power supply
Sony 12-inch color monitor
Tektronix test and measurement instrumentation
TM506 power module (2)
SC502 oscilloscope (2)
DV501 digital volt meter (2)
FG502 function generator (2)
FG504 high performance function generator
PG501 pulse generator
AM501 high gain DC amplifier (3)
PS503 power supply (3).

SMART PRODUCT DESIGN LABORATORY

Terman Engineering Center, room 577, Stanford University.

Purpose The Smart Product Design Laboratory (SPDL), is an educational facility within the Center for Design Research for teaching electromechanical design engineers the philosophy, theory, and practice of using microprocessor technology in their products. The lab supports an aggressive three-quarter course in the Mechanical Engineering Design Division that gives students the opportunity to identify, design, and prototype a smart product.

Resources

Hardware
IBM PS/2-50 microcomputer systems (14)
Apple MacIntosh systems (6)
Prolog Z-80 based STD-bus target development computers (9)
IBM 7470 plotters (2)
Epson MX-80 & IBM Color Graphics printers
Apple Laserwriter & Imagewriter printers
Various in-house peripheral controllers
Oscilloscopes and other test equipment.

Software
MS DOS, and UCSD P-System operating systems
LMI Forth (XTs), MACH-1 Forth (MacIntoshes)
Basic, Fortran, Pascal, Assembly languages
Multiplan, Symphony, Excel, Word, and other word processors, text editors, and communication programs.

ENGINEERING STRUCTURES AND BIOMECHANICS LABORATORIES

School of Engineering, Stanford University.

Purpose The Structures Laboratory is the center for research for faculty interested in the mechanical properties of materials and structures. Complementing this laboratory is the Biomechanics Laboratory for specific research on the structure and properties of the skeletal system.

Resources

Structures Laboratory

MTS electro-hydraulic testing systems:
22 kips (100 kN) low-rate frame
22 kips (100 kN) high-rate frame
Horizontal earthquake simulator
Vertical earthquake simulator
Redlake Labs high speed camera (up to 11,000 fps)
Endevco signal conditioning (25 channels)
Honeywell 5600 AC/DC tape recorder (14 channels)
Honeywell Visicorder
H-P 5423A structural dynamics analyzer
H-P 8245B plotter printer.

Biomechanics Laboratory

MTS 810 electro-hydraulic testing system (22 kips, 100 kN)
MTS 858 electro-hydraulic testing system (5.5 kips, 24 kN)
Emco Maximat Mentor 10 lathe/mill
Sears Craftsman band saw (12 in), Buehler rotary polisher (12 in)
Vishay 2120 DC strain-guage conditioners (16 channels)
Honeywell strip-chart recorders: 1200 (2-channel), 1800 (8-channel)
H-P 7046A x-y plotter
H-P 3575A gain-phase meter
Function generators: H-P 203A, H-P 3311A
H-P 6218A power supply
Endevco 2718A shock amplifier
Princeton Applied Research 5204 lock-in analyzer
Krohn-Hite 3323 electrical filter (2-channel)
Multimeters: Fluke 8000A, 8060A
Tektronix 455 oscilloscope w/camera
Validyne digital conditioning (14 ch)
Force dynamometers (4) with 6 degrees of freedom
Displacement transducer with 6 degrees of freedom
Force dynamometer calibration stand
Mitutoyo 3058E dial indicators (5)
Starrett 640J dial depth gauge.

Histological Laboratory

Bransonic 220 ultrasonic cleaner
Ohaus solution balance (45 lb)
Torbal EA-1 torsion balance
Laser Technology wire saw
Zeiss Universal microscope w/camera
Bausch and Lomb dissecting microscope
Nikon Multiphot low-magnification camera.

ELECTROMYOGRAPHY AND APPLIED CLINICAL NEUROPHYSIOLOGY LABORATORY

Stanford University Medical Center

Purpose The Electromyography and Applied Clinical Neuro-physiology Laboratory supports the collection and analysis of clinical electrophysiology data from the human neuromuscular system.

Resources

TECA TE-4 electromyograph
4 channel amplifiers
DC amplifier
Dual voltage stimulators
Mid-signal trigger/delay unit
Digital signal averager
2-channel direct tape recorder.

DISA 1500 electromyograph
4 channels
Voltage/current stimulators
Digital signal averager.

Nicolet 1170 4-channel signal averaging system
Visual, auditory and somatosensory stimulators.

Nicolet Pathfinder-II signal averaging system
8-channel capability
somatosensory stimulator
128k 20-bit word memory
10 MB Winchester disk
Fortran Development System
HP graphics plotter
NEC line printer.

Nicolet 1070 4-channel signal averaging system
Nicolet Viking electromyograph
Hewlett-Packard instrumentation FM tape recorder.

DEC PDP-11/34A computer
48k word memory
16-ch 12-bit A/D, 2-ch D/A
floating-point arithmetic unit
dual discs, 7.5 MB capacity
80 MB winchester disc
Time/Data A.C.E.
9-track, 800 BPI digital magnetic tape
Tektronix graphics terminal
Versatec electrostatic printer/plotter
UNIX and RT-11 operating systems
Fortran-IV, macro-assembler and TSL.

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SCIENTIFIC PRESENTATIONS The following is a cumulative list of scientific presentations given by RR&D Center members at scientific congresses and conferences. In many cases abstracts or short papers have been published in conference proceedings.

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